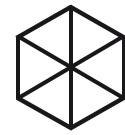




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# Rethinking Variation in Social Cognition: Gaze Following Across Individuals, Ages, and Communities

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# Abstract

Social cognition enables children to navigate the social world and engage meaningfully with others. As they develop, children become increasingly skilled at predicting and interpreting others' mental states – such as beliefs, desires, and intentions – and at understanding different perspectives. The bedrock of many social-cognitive abilities is gaze following: Identifying another's visual focus of attention is valuable for extracting information from the environment and determining the internal states of other agents. The emergence of gaze following has been thoroughly studied on a group level in children from the Global North. Yet we know little about individual-level and cross-cultural variation. This is problematic because many developmental theories emphasize the role of social interaction in the development of social cognition – and the frequency and characteristics of social interactions vary substantially across individuals and cultures. This dissertation aims to highlight the prevalence and importance of variation in social cognition based on the example of gaze following. In four studies, we have designed a new gaze following task and applied it to capture individual- and community-level variation in this core social-cognitive ability.

Study I focused on the development and psychometric assessment of a new task, the TANGO (Task for Assessing iNdividual Differences in Gaze understanding-Open). An animated interactive picture book asked participants to locate a balloon with the help of an agent's gaze cue. A spatial layout allowed for a discrete and continuous measure of participants' imprecision in locating the gaze of the agent. We implemented a new interactive web application that works across devices and enables supervised and unsupervised in-person and remote testing. We found substantial individual differences in a child ( $N = 387$  from Leipzig, Germany) and an adult ( $N = 236$ , international remote) sample. Good psychometric properties, in the form of high internal consistency and test-retest reliability, indicated highly systematic variation. Relationships with family-level variables and children's language abilities underline the validity of the task. Together, the results show how the TANGO is a reliable and valid tool to assess individual differences in gaze following.

Study II applied the TANGO to answer three research questions focusing on individual differences in gaze following. First, we aimed to assess how gaze following develops across the lifespan. For this, we examined imprecision in gaze following in children, teenagers, and adults ( $N = 478$  3- to 19-year-olds from Leipzig, Germany, and  $N = 240$  20- to 80-year-old international, remotely tested adults). During preschool years, children became increasingly precise in gaze following and reached adult-like performance at around ten years of age. Young adults reached the highest precision levels, which slightly declined toward old age. Across all age groups, participants showed individual differences. Second, we were interested in how people cognitively process gaze cues and how different imprecision levels in gaze following could be explained. With the help of a computational cognitive model, we conceptualized individual differences in gaze following on a process level ( $N = 60$  3- to 5-year-olds and  $N = 50$  adults). Participants were modeled to observe the agent's pupil location within

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the eye and estimate the resulting pupil angles and gaze vectors. This inferential estimation process was assumed to be noisy. Individual differences and the development of gaze following were described as varying levels in the precision to estimate pupil angles. A model comparison with two alternative models and a signature pattern in the data yielded strong evidence for the proposed gaze model. Third, we intended to study how other (social-) cognitive abilities relate to gaze following. We experimentally tested the model's assumption describing gaze following as a form of social vector estimation ( $N = 102$  4- to 5-year-olds). Individuals' gaze-following abilities correlated with their precision in non-social vector estimation and visual perspective-taking. Other Theory of Mind tasks did not correlate. These findings suggest that gaze following relies on attention to social as well as spatial components.

Study III aimed at examining the universality and variability of gaze following and to broaden our perspective beyond samples coming from the Global North. We presented the largest cross-cultural study on children's gaze following abilities to date ( $N = 1377$ ): We studied 2.5- to 11-year-olds from 17 different urban/rural communities in Argentina, China, the Republic of the Congo, Germany, India, Mexico, Namibia, Nigeria, New Zealand, Sambia, Türkiye, the UK, Uganda, and the USA. Across communities, we found similar substantial developmental gains: With increasing age, children became more precise in locating the gaze focus of another agent. Absolute differences in imprecision levels could be partially explained by children's familiarity with the data collection device (tablet/touchscreen). In all communities, we found the same signature pattern in the data, and comparisons to alternative models provided strong evidence for the previously proposed gaze model. Despite existing individual- and community-level variation in observable behavior, this speaks for a universal mechanism in how children follow gaze.

Study IV describes the design process of the TANGO-CC, the cross-cultural gaze following task used in Study III. We provided an open-source website and tutorial for researchers to adapt the TANGO-CC to their needs (e.g., selecting language and stimuli). Most importantly, we further aimed to assess how the psychometric properties of the TANGO(-CC) generalize across diverse communities. While we previously established the task's validity and reliability in one community from the Global North (Leipzig, Germany; Study 1), we re-analyzed the cross-cultural data set of Study III. We found individual differences across communities and within-community variation outweighed between-community variation. Split-half reliability estimates for each community were satisfactory. These findings indicated the TANGO-CC's suitability for cross-cultural research.

Taken together, this dissertation takes an innovative, extensive, multifaceted perspective on gaze following and the cognitive processes behind it. It highlights how combining individual differences, cross-cultural research, and formal modeling will enable us to explore the development and structure of our core social-cognitive processes in greater detail. By openly providing all materials and data, we aim to foster further research in this direction and encourage the scientific community to rethink variation in social cognition.

# Zusammenfassung

Soziale Kognition ermöglicht es Kindern, sich in der sozialen Welt zurechtzufinden und angemessen mit anderen zu interagieren. Im Laufe ihrer Entwicklung werden Kinder immer geschickter darin, die mentalen Zustände anderer - wie Überzeugungen, Wünsche und Absichten - vorherzusagen, zu interpretieren und unterschiedliche Perspektiven zu verstehen. Die Grundlage vieler sozial-kognitiver Fähigkeiten ist die Blickverfolgung: Den visuellen Aufmerksamkeitsfokus eines Gegenübers zu identifizieren ist wegweisend, um Informationen aus der Umwelt und über die mentalen Zustände anderer zu gewinnen. Die Blickverfolgung ist auf Gruppenebene bei Kindern aus dem Globalen Norden gründlich untersucht. Jedoch wissen wir nur wenig über individuelle und kulturübergreifende Unterschiede. Dies ist problematisch, da viele Entwicklungstheorien die Rolle der sozialen Interaktion bei der Entwicklung sozialer Kognition betonen und die Häufigkeit und Merkmale sozialer Interaktionen zwischen Individuen und Kulturen erheblich variieren. Diese Dissertation soll die Bedeutsamkeit von Variation in der sozialen Kognition am Beispiel der Blickverfolgung aufzeigen. In vier Studien haben wir eine neue Aufgabe zur Blickverfolgung entwickelt und angewandt, um Variation in dieser zentralen sozial-kognitiven Fähigkeit auf individueller und Gemeinschaftsebene zu erfassen.

Studie I befasste sich mit der Entwicklung und psychometrischen Überprüfung der neuen Aufgabe, dem TANGO (Task for Assessing iNdividual Differences in Gaze understanding-Open). Ein animiertes interaktives Bilderbuch forderte die Teilnehmenden auf, einen Luftballon zu finden, in dem sie der Blickrichtung eines Anderen folgten. Durch ein räumliches Layout konnten wir die Ungenauigkeit von Teilnehmenden in der Blickverfolgung diskret und kontinuierlich messen. Dafür haben wir eine neue interaktive Web-Anwendung implementiert, die geräteübergreifend funktioniert und Datenerhebungen beaufsichtigt vor Ort und unbeaufsichtigt unterwegs ermöglicht. Wir fanden erhebliche individuelle Unterschiede in einer Kinder- ( $N = 387$  aus Leipzig, Deutschland) und einer Erwachsenenstichprobe ( $N = 236$  international verteilt). Die psychometrischen Eigenschaften, basierend auf interner Konsistenz und Test-Retest-Reliabilität, wiesen auf sehr systematische Variation hin. Zusammenhänge mit Variablen auf familiärer Ebene und sprachlichen Fähigkeiten unterstreichen die Validität der Aufgabe. Insgesamt ist der TANGO ein zuverlässiges und valides Instrument, um individuelle Unterschiede in der Blickverfolgung zu erfassen.

In Studie II haben wir den TANGO auf drei Forschungsfragen angewandt, die sich auf individuelle Unterschiede in der Blickverfolgung konzentrieren. Erstens wollten wir herausfinden, wie sich die Blickverfolgung über die Lebensspanne entwickelt. Zu diesem Zweck untersuchten wir die Ungenauigkeit der Blickverfolgung bei Kindern, Jugendlichen und Erwachsenen ( $N = 478$  3- bis 19-jährige Kinder aus Leipzig, Deutschland und  $N = 240$  20- bis 80-jährige internationale Erwachsene). Im Laufe des Vorschulalters wurden Kinder zunehmend präziser, den Blickrichtungen anderer zu folgen. Junge Erwachsene erreichten die höchste Genauigkeit, die mit zunehmendem Alter leicht

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abnahmen. Über alle Altersgruppen hinweg zeigten die Teilnehmenden individuelle Unterschiede. Zweitens interessierten wir uns dafür, wie Menschen Blickhinweise kognitiv verarbeiten und wie unterschiedliche Ungenauigkeiten bei der Blickverfolgung erklärt werden können. Mit Hilfe eines kognitiven Computermodells konzeptualisierten wir individuelle Unterschiede bei der Blickverfolgung auf Prozessebene ( $N = 60$  3- bis 5-Jährige und  $N = 50$  Erwachsene). Das Modell nimmt an, dass die Teilnehmenden die Position der Pupille im Auge des Gegenübers beobachten und die daraus resultierenden Pupillenwinkel und Blickvektoren schätzen. Dieser inferentielle Schätzprozess kann fehlerhaft sein. Individuelle Unterschiede und die Altersentwicklung in der Blickverfolgung wurden modelliert durch unterschiedlich genaue Schätzungen der Pupillenwinkel. Durch einen Modellvergleich mit zwei alternativen Modellen und einem Signaturmuster in den Daten konnte das vorgeschlagene Blickmodell klar bestätigt werden. Drittens wollten wir untersuchen, wie andere (sozial-) kognitive Fähigkeiten mit der Blickverfolgung zusammenhängen. Wir testeten experimentell die Modellannahme, die Blickverfolgung als eine Form der sozialen Vektorschätzung beschreibt ( $N = 102$  4- bis 5-Jährige). Die Genauigkeit in der Blickverfolgung korrelierte mit einer nicht-sozialen Vektorschätzaufgabe und der visuellen Perspektivübernahme. Andere Theory-of-Mind-Aufgaben korrelierten nicht. Die Ergebnisse deuten darauf hin, dass die Blickverfolgung von der Aufmerksamkeit auf soziale und räumliche Aspekte abhängt.

Studie III zielte darauf ab, die Universalität und Variabilität der Blickverfolgung zu untersuchen und unsere Perspektive über Stichproben des Globalen Nordens hinaus zu erweitern. Diese Studie stellt die bisher größte kulturübergreifende Studie über Blickverfolgung von Kindern dar ( $N = 1377$ ): Wir untersuchten 2,5- bis 11-Jährige aus 17 verschiedenen städtischen und ländlichen Gemeinschaften in Argentinien, China, der Republik Kongo, Deutschland, Indien, Mexiko, Namibia, Nigeria, Neuseeland, Sambia, der Türkei, Großbritannien, Uganda und den USA. In allen Gemeinschaften fanden wir ähnliche Entwicklungsabläufe: Mit zunehmendem Alter wurden die Kinder präziser darin, den Aufmerksamkeitsfokus eines Gegenübers zu bestimmen. Die absoluten Unterschiede in der Ungenauigkeit konnten teilweise durch die Vertrautheit der Kinder mit dem Endgerät (Tablet/Touchscreen) erklärt werden. In allen Gemeinschaften fanden wir das gleiche charakteristische Muster in den Daten, und Vergleiche mit alternativen Modellen lieferten starke Evidenz für das zuvor vorgeschlagene kognitive Modell. Trotz vorhandener individueller und gemeinschaftlicher Verhaltensunterschiede spricht dies für einen universellen Prozess, wie Kinder der Blickrichtung anderer folgen.

Studie IV beschreibt den Entwicklungsprozess des TANGO-CC – der kulturübergreifenden Blickverfolgungsaufgabe, die wir in Studie III verwendet haben. Wir präsentieren eine Open-Source-Web-Anwendung und ein Tutorial für Forschende, damit diese den TANGO-CC an ihre Bedürfnisse anpassen können (z.B. durch die Wahl der Sprache und der Stimuli). Das wichtigste Ziel unserer Studie war es, die psychometrischen Eigenschaften des TANGO(-CC) in verschiedenen Gemeinschaften zu untersuchen. Während wir die Validität und Reliabilität der Aufgabe bereits in einer Gemeinschaft des globalen Nordens (Leipzig, Deutschland; Studie 1) nachgewiesen hatten, analysierten wir die kulturübergreifenden Daten der Studie III daraufhingehend erneut. Wir fanden heraus, dass es in

allen Gemeinschaften individuelle Unterschiede gab und dass die Variation innerhalb der Gemeinschaften größer waren als die Variation zwischen den Gemeinschaften. In allen Gemeinschaften fanden wir zufriedenstellende Werte in den Split-Half-Reliabilitätsschätzungen. Diese Ergebnisse zeigen, dass der TANGO-CC in der kulturübergreifenden Forschung angewendet werden kann.

Zusammenfassend bietet diese Dissertation eine innovative und vielschichtige Perspektive auf die Entwicklung der Blickverfolgung und die dahinterstehenden kognitiven Prozesse. Sie hebt hervor, wie die Kombination von individuellen Unterschieden, kulturübergreifender Forschung und formaler Modellierung es uns ermöglichen wird, die Entwicklung und Struktur unserer zentralen sozial-kognitiven Prozesse genauer zu untersuchen. Indem wir all unsere Materialien und Daten offen zur Verfügung stellen, wollen wir weitere Forschung in dieser Richtung fördern und die wissenschaftliche Gemeinschaft dazu ermutigen, Variation in Sozialer Kognition neu zu überdenken.



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# List of Abbreviations

**ASD** Autism Spectrum Disorder

**CDI** MacArthur-Bates Communicative Development Inventories

**CI** Confidence Interval

**CLT** Cross-linguistic Lexical Task

**Crl** Credible Interval

**DB** Diverse Beliefs

**DD** Diverse Desires

**DISKO** Differentiating Incomplete States of Knowledge-Open

**DSM-5** Diagnostic and Statistical Manual of Mental Disorders, 5th edition

**FB** False Belief

**GLMM** Generalized Linear Mixed Model

**GSAP** GreenSock Animation Platform

**HE** Hidden Emotions

**IRT** Item Response Theory

**KA** Knowledge Access

**PREVIC** Parent Report of Expressive Vocabulary in Children

**SVG** Scalable Vector Graphics

**TANGO** Task for Assessing iNdividual differences in Gaze understanding-Open

**TANGO-CC** TANGO-Cross-Cultural

**ToM** Theory of Mind

**WEIRD** Western, Educated, Industrialized, Rich, Democratic

**oREV** open Receptive Vocabulary task



# **Authorship Note**

In this dissertation, the plural pronoun “we” highlights the collaborative efforts within the presented scientific projects. The contributions of all co-authors of the included manuscripts are transparently and accurately attributed using the Contributor Roles Taxonomy (CRediT; <https://credit.niso.org>) and can be found for each respective manuscript in Appendix A. In text sections where the primary responsible person is not explicitly defined, “we” refers to the efforts of this dissertation’s author alone, as the plural pronoun “we” reflects standard practice in psychological scientific writings. This use does not diminish the author’s significance in conceptualizing, executing, documenting, and interpreting the presented research. The singular pronoun “I” explicitly denotes personal opinions, reflections, and decisions regarding this dissertation’s theoretical framework paper and its structure.



# **Structure of This Dissertation**

This dissertation is part of an overarching, ongoing project led by Prof. Dr. Manuel Bohn (Leuphana University Lüneburg) and Prof. Dr. Daniel Haun (Max Planck Institute for Evolutionary Anthropology Leipzig). The project aims to create a new task battery for social cognition that will capture individual differences in children from diverse communities. The present thesis details the steps that have already been taken in this endeavor: During my time as a doctoral candidate, we have designed, implemented, and validated the first task of the battery, focusing on the fundamental social-cognitive ability of gaze following.

The present dissertation takes a comprehensive approach to developing the new gaze-following task, addressing it both from a theoretical and a methodological perspective. The first part of the introduction will focus on the psychological construct(s) underlying gaze following. I will describe the importance of human social cognition and its milestones during child development. I will continue to elaborate on the construct of gaze following and its developmental milestones. I will end both these sections by considering studies that focus on individual differences and, subsequently, studies conducted cross-culturally. The second part of the introduction will focus on the methodological considerations for constructing a new task (battery). I will establish the need for individual differences- and cross-cultural research perspectives, examine existing social cognition measures with regards to this identified need, and propose a potential way forward for measures of social-cognitive development.

The next chapter on the general approach of this dissertation will describe the aims of the four included publications. I will outline the methodological decisions we made while developing the new gaze-following task.

In the general discussion, I will summarize the findings of the four included studies and highlight their theoretical and methodological contributions to developmental psychology. I will discuss their limitations and provide an outlook for future studies in social cognition, focusing on individual differences and cross-cultural research.



# 1 General Introduction

In 1977, NASA launched the Voyager 1 and 2 spacecraft with a golden time capsule as a bold interstellar greeting. This Golden Record aimed to present the essence of Earth and humanity to potential extraterrestrial receivers. It included natural sounds, music from different cultures, greetings in 55 languages, and a photographic gallery. Among several pictures of mathematical formulas, scientific diagrams, and planetary constellations, a large proportion of the included photos focused on the most fundamental human experiences. These pictures showed humans hunting and playing music together, eating and arguing at a full dinner table, collaboratively rowing a boat, competitively running against each other in marathons, nursing their children, and teaching them how to write. Strikingly, humans were rarely presented alone. These photographs, attempting to capture a comprehensive snapshot of Earth's environment, focused on humans interacting with each other in social and cultural groups.

Our ability to engage with one another in social interaction and communication has been highlighted in prominent evolutionary and psychological theories (e.g., Dunbar, 1998; Henrich, 2015; Henrich & Henrich, 2007; Herrmann et al., 2010; Heyes, 2012, 2018; Tomasello, 2019; Tomasello & Rakoczy, 2003). Contrary to other mammals that act on others' observable actions, humans pay attention to each others' minds (Slaughter, 2015), and have been described as "ultra-social primates" (Grossmann, 2022, p. 1). We perceive other agents in profoundly different ways than other entities in the world (Rakoczy, 2022), and "social cues are among the most complex stimuli that the human brain has to process" (Beaudoin et al., 2020, p. 14). We form social bonds (e.g., Bowlby, 1958), live (mostly) cooperatively (e.g., Tomasello, 2020), exchange information, and learn through observing others (e.g., Csibra & Gergely, 2009). By relying on these strategies, knowledge and skills could be passed on from generation to generation, which could not have been acquired by one single individual (Henrich, 2015).

A seminal paper by Herrmann et al. (2007) tested the hypothesis that humans have unparalleled social-cognitive abilities and administered a cognitive test battery with 16 different tasks to chimpanzees, orangutans, and 2.5-year-old human infants. Indeed, the results showed that all three groups showed similar cognitive abilities within the physical realm (space, quantities, causality), while human infants outperformed the chimpanzees and orangutans when it came to the social

world (social learning, communication, Theory of Mind (ToM)). Sociality – and the cognitive abilities enabling it – might very well be humans' superpower.

In 2013, the importance of social cognition was officially recognized by the standard classification framework for mental disorders in the United States, the Diagnostic and Statistical Manual of Mental Disorders, 5th edition (DSM-5) (American Psychiatric Association, 2013), which categorized social cognition as one of six core functional domains that can be affected by a neurocognitive disorder. The number of publications in different psychological domains highlights that many psychologists agree on the importance of social cognition. A quick search on the APA PsycNet (on June 25, 2024, at 17:00 CET) revealed 28,594 results for the search term “social cognition,” while only 3,095 results appeared for “spatial cognition” and 95 appeared for “physical cognition.”

## 1.1 Social Cognition

### 1.1.1 Terminology

So far, I have argued for the importance of human social-cognitive abilities. Before going deeper into the developmental literature on social cognition, I want to clarify the terminology: What is *social cognition*? Interestingly, most psychologists do not agree on one accepted definition (Beaudoin et al., 2020). Rather, cynical tongues might say there are as many definitions of social cognition as there are research articles on it. As Ostrom put it in the *Handbook of Social Cognition*: “I regard single-sentence definitions of social cognition to be slightly offensive [...]. It would be more accurate to say that my preferred definition is the entire Handbook of Social Cognition, both this and the first edition combined” (Ostrom, 1994, p. vii). Indeed, researchers have argued that the non-specific and heterogeneous vocabulary hinders empirical and theoretical advancement: Sometimes, a single concept is described by several different labels (i.e., convergence of meaning), while other concepts share the same label but refer to different constructs (i.e., divergence of meaning) (Quesque et al., 2024; Quesque & Rossetti, 2020).

To illuminate what developmental psychologists understand under the term social cognition, we conducted a short expert survey in Autumn/Winter 2020 (see Appendix C). We distributed an online questionnaire via personal contacts and emailing lists (e.g., cogdevsoc mailing list), and 100

researchers broadly working in cognitive, comparative, cross-cultural, and/or developmental psychology completed it. First, we asked experts to define social cognition as a psychological construct. Exactly one-third of the sample (33%, n = 33) chose a definition by Glynn & Watkiss (2016): “Social cognition is the process by which actors, at individual or collective levels, decode and encode their social world, using mental models, knowledge structures and cultural understandings to process information, extract meaning and determine appropriate action” (p. 1). The next two most frequently chosen definitions similarly focused on information processing aspects in environments enlivened with other agents (“[...] encompasses all the information-processing mechanisms that underlie how people capture, process, store, and apply information about others to navigate social situations” (Decety, 2020, p. ix) (21%, n = 21); “[...] is concerned with the study of the thought processes, both implicit and explicit, through which humans attain understanding of self, others, and their environment” (Moskowitz, 2013, p. 1) (10%, n = 10)). In the next step, we asked experts to name which dimensions they mentioned most often when discussing or writing about social cognition. The dimensions that were chosen by more than half of the experts were beliefs, knowledge, perspective-taking, and intentions. To conclude, social cognition is often understood as a construct that involves information processing in social environments, with a focus on mental states such as beliefs, knowledge, perspectives, and intentions.

When defining social cognition, a distinction must be made to the term ToM (also referred to as mentalizing, folk psychology, or psychological reasoning), one of the most studied research areas in developmental cognitive science (Sabbagh & Paulus, 2018). While the terms are sometimes used synonymously, social cognition is the umbrella term encompassing ToM (Beaudoin et al., 2020; Quesque et al., 2024). The term ToM was first coined by the primatologists Premack & Woodruff (1978) and is defined as the ability to view oneself and others as “rational subjects with individual perspectives on the world” (Rakoczy, 2022, p. 223). It describes a system organized around mental states to explain and predict the behavior of agents. In other words, we try to understand actions by representing and attributing percepts, desires, and beliefs to ourselves and others, summarized by Wellman as follows: “In our everyday thinking we construe people as engaging in acts they *think* will get them what they *want*” (Wellman, 2013, p. 69). A core concept involved in ToM is *meta-representation*: representing the content and manner in which agents represent the world from their perspective (Rakoczy, 2022). Meta-representational abilities rely on understanding that mental states hold information independent of the real world. Consequently, individuals need to comprehend that mental states can (1) differ between individuals, (2) conflict with their own mental states, (3) be inaccurate

or false, and (4) be aspectual (i.e., objects can be represented under certain perspectives) (Rakoczy, 2022). ToM has been traditionally viewed as a unitary construct, but recent neurophysiological evidence suggests a multidimensional structure (Fu et al., 2023; Slaughter & Repacholi, 2003). Beaudoin et al. (2020) have, for example, identified seven categories within ToM, namely “emotions, desires, intentions, percepts, knowledge, beliefs, and mentalistic understanding of non-literal communication” (p. 5), and Fu et al. (2023) have proposed the construct dimensions of cognitive (e.g., beliefs) vs. affective (e.g., emotions), and intra- (i.e., concerning yourself) vs. interpersonal (i.e., concerning other agents). Taken together, ToM is a part of social cognition focusing on meta-representation of mental states, while social cognition is the broader construct encompassing all information processing in social environments.

### 1.1.2 Developmental Milestones

Human infants do not come into the world already possessing mature social cognition (Tomasello, 2020). Much of developmental psychology research studies how children acquire the social-cognitive abilities which are needed to become full members of our society.

The development of social cognition starts with social perception: Newborns are preferentially interested in faces and biological motion (Simion et al., 2008; Simion & Giorgio, 2015). By two months, infants begin to smile socially and engage in proto-conversational social interactions (Rochat et al., 1999). An understanding of agency and others’ intentions follows. For example, six-month-old infants expect that another agent acts in a goal-directed way (Woodward, 1998). From 9 months onward, infants recognize contingencies in actions and realize they are being imitated (Agnetta & Rochat, 2004). They react differently to similar behaviors if those behaviors have different intentions (e.g., unwilling vs. unable agents, Behne, Carpenter, Call, et al., 2005). In the second half of the first year, infants can judge the rationality of goal-directed actions (Gergely et al., 1995). Fourteen-month-olds imitate other actions in a rational way (Gergely et al., 2002). One-and-a-half-year-olds imitate what an agent intended to do and not what they actually did (Meltzoff, 1995). At the same age, children help others by completing their previously failed actions (Warneken & Tomasello, 2006). Children between 18 and 21 months start to perform synchronous imitation, pretend play and recognize themselves in mirrors (touching their own face, not the mirror image) (Nielsen & Dissanayake, 2004).

After this so-called perception-goal psychology emerged in infancy, belief-desire psychology develops (Rakoczy, 2022). Around 18 months, children can recognize the subjectivity of desires and their relation to emotion (Repacholi & Gopnik, 1997). In their second year of life, children engage in Level I perspective-taking, in which they understand *that* different persons perceive objects differently (Moll & Tomasello, 2006). Level II perspective-taking, which involves *how* other agents perceive objects, emerges one year later, around three years of age (Moll & Meltzoff, 2011). At this age, children start to reference mental states by using terms such as *want*, *think*, *know*, *pretend*, and *dream* in their utterances (Furrow et al., 1992; Shatz et al., 1983). Three-year-olds understand that perceptual access leads to knowledge: They understand that a person who has looked into a box knows its content (Hogrefe et al., 1986). Most four-year-olds understand that they themselves and other agents can have a False Belief (FB) (Gopnik & Astington, 1988; Wellman et al., 2001; Wimmer & Perner, 1983): They grasp that how an agent acts depends not only on reality itself but also on what the agent believes (Wellman, 2024). Interestingly, recent non-verbal measures (e.g., violation-of-expectation or anticipatory looking paradigms) have argued that infants as young as 15 months show an understanding of FB (Onishi & Baillargeon, 2005; Senju, 2012; Southgate et al., 2007). However, the replicability, reliability, and validity of these implicit measures have been questioned by others (Dörrenberg et al., 2018; Kulke et al., 2018; Sabbagh & Paulus, 2018) as well as the authors of the original findings (Kampis et al., 2021).

In later years, children master higher-order, recursive ToM tasks (Liddle & Nettle, 2007) and start recognizing faux pas (Baron-Cohen et al., 1999). Five-year-olds begin to understand ironic speakers, but only nine- to ten-year-olds can accurately distinguish irony and sarcasm (Glenwright & Pexman, 2010).

Taken together, children show very early preferences for social stimuli, develop basic social-cognitive abilities in perception, goal, and intentionality understanding around nine months, and refine these fundamental abilities between one and three years of age. At four to five years, children show more complex, meta-representational understandings of beliefs and desires and refine these, in turn, in the following years to gain a recursive, higher-order ToM (Rakoczy, 2022). Importantly, many of these established findings rely on group-level averages of children based in the Global North (Nielsen et al., 2017) – these shortcomings will be further discussed in later sections of the present dissertation.

### 1.1.3 Individual Differences

Many decades of research in social cognition have taught us much about developmental milestones and the average age at which children show certain social-cognitive abilities (for a review, see Rakoczy, 2022, or the section above). Yet anyone who has ever interacted with children notices that peers can differ substantially in their abilities. For example, one child could barely understand diverse desires, while another child from the same age group could already identify hidden emotions (Slaughter, 2015).

*Individual differences* describe the features in which agents vary from one another (American Psychological Association, n.d.-a). *Inter-individual* differences focus on the variability *between* children, while *intra-individual* differences focus on the variability *within* the same child. Asendorpf (1992) has argued that inter-individual differences are often interpreted as trait-like characteristics (e.g., personality) that are more or less stable over time, while intra-individual differences might capture state-like characteristics (e.g., motivation) or development within a given construct. The present thesis and the associated publications focus on inter-individual differences, often abbreviated to individual differences.

Studies on individual differences in social cognition mainly focus on the social-cognitive ability in question and its connection to (1) family variables, (2) social behavioral measures, and (3) other cognitive abilities (Slaughter & Repacholi, 2003). As a quick summary, children's social-cognitive abilities impact their social lives and real-life outcomes (Hughes & Leekam, 2004; Rakoczy, 2022). For example, children with sophisticated social cognition show higher levels of prosocial behavior (Imuta et al., 2016), peer popularity (Slaughter et al., 2015), and mutual friendships (Fink, Begeer, Peterson, Slaughter, & de Rosnay, 2015; Fink, Begeer, Peterson, Slaughter, & De Rosnay, 2015). High ToM scores relate to increased communication abilities such as persuasive skills (Slaughter et al., 2013) and academic achievements (Binnie, 2005; Lecce et al., 2017). Additionally, some negative, egoistic, and manipulative behaviors, such as lying, deceiving, and bullying, also seem to profit from advanced social-cognitive abilities (Ding et al., 2015; Gasser & Keller, 2009; Rakoczy, 2022; Talwar & Lee, 2008). In contrast, children who struggle with social cognition might experience challenges in their social competencies. Decreased ToM performance has been found in children with language impairments (Nilsson & de López, 2016; Stanzione & Schick, 2014) and atypical developmental pathways, including Autism Spectrum Disorder (ASD) (Baron-Cohen, 2000), attention deficit hyperactivity disorder (Pineda-Alhucema et al., 2018), oppositional defiant disorder, mood disorders, eating

disorders, or obsessive-compulsive disorder (Korkmaz, 2011; Szamburska-Lewandowska et al., 2021). Importantly, most of these studies are correlational, so the direction of the cause and effect is often unclear (Slaughter, 2015).

### 1.1.4 Cross-Cultural Research

While the majority of (developmental) psychology research is based on samples from the Global North (Apicella et al., 2020; Gutchess & Rajaram, 2023; Henrich et al., 2010; Kline et al., 2018; Thalmayer et al., 2021), some studies focus on how social and cultural factors influence child development. Wellman (2013) has argued that children's social-cognitive development is a particularly informative domain to assess how people worldwide resemble and differ from one another. Several cross-cultural studies have documented substantial variation in this domain (Miller et al., 2018; Wellman, 2014), and indeed, Quesque et al. (2022) found that country-level differences account for more than one-fifth of the variance in participants' understanding of others' thoughts and emotions. An example comes from Wellman et al. (2011), who showed that Chinese children understood Knowledge Access (KA) at an earlier age than U.S. American children (who, in turn, understood Diverse Beliefs (DB) earlier). Cultural values (e.g., individualist vs. collectivist) and caregiver-child conversations emphasizing different mental states (e.g., knowing vs. thinking) might explain these differences in the ToM sequence (Johnston & Wong, 2002; however, see Ilgaz et al., 2022). Evidence for this hypothesis also comes from a study conducted in New Zealand and Iran by Taumoepeau et al. (2019) who found that child-directed mental state talk was related to children's ToM.

An interesting observation has been the so-called *Opacity Doctrine* (Dixson et al., 2018): Communities on remote Pacific islands avoid reasoning or talking about the mental states of others as this is deemed inappropriate and impossible. The inclination to not speculate about others' mental states may influence the onset, developmental trajectory, and/or expression of children's ToM abilities. Mayer & Träuble (2013) found a delayed onset of FB understanding in Samoan children, with the majority of children being eight years or older when passing the tasks. Similarly, Dixson et al. (2018) found that ni-Vanuatu children, especially in rural areas, passed FB tasks later than their Western counterparts.

Despite these documented cross-cultural differences, some studies also revealed similarities in social-cognitive development between diverse communities. For example, Barrett et al. (2013) studied early FB understanding in three traditional, small-scale, non-Western communities. They found that one-

to four-year-old children from Salar (China), Shuar/Colono (Ecuador), and Yasawan (Fiji) communities showed similar response patterns in three spontaneous looking time measures to classical studies conducted in Western communities (Barrett et al., 2013). Callaghan et al. (2005) have shown that children from Canada, Samoa, India, and Peru show similar developmental trajectories in FB understanding, with some variations at which specific age between three and five years the majority of children pass the task.

In sum, the order and timing in which children pass classical ToM tasks (i.e., Diverse Desires (DD), DB, KA, content FB, Hidden Emotions (HE)) vary between different communities, which might rely on differences in large-scale cultural, and small scale family factors (Rakoczy, 2022; Wellman, 2013). And yet “children go from consistently wrong to consistently correct worldwide, typically in the preschool years” (Wellman, 2024). Still, cross-cultural research constitutes only a small fraction of all articles published on social cognition and often covers only specific aspects such as children’s ToM understanding.

## 1.2 Gaze Following

This dissertation, with its included publications, focuses on one specific aspect of social cognition: Gaze following. I will first introduce why eye gaze is important in social cognition, clarify the terminology used in the field of gaze following, and then present developmental milestones, individual differences, and cross-cultural variation in gaze following.

### 1.2.1 Relevance and Functions of Eye Gaze

In contrast to other primates, human eyes have a distinctive morphology: They have (1) a depigmented, white sclera, (2) a large exposition of the sclera compared to the eye outline, (3) a stark color contrast between the sclera, the black pupil, the colored iris, and (4) are elongated in the horizontal direction (Kobayashi & Kohshima, 1997, 2001). These characteristics heighten the visibility of gaze direction under visually challenging conditions (Kano et al., 2022). Furthermore, the ratio of the visible sclera on each side of the pupil might enable humans to detect gaze direction (Anstis et al., 1969; Symons et al., 2004; Todorović, 2006). The *cooperative eye hypothesis* suggests that the morphology of the human eye specifically evolved to facilitate gaze following and thereby, communication and cooperation (Tomasello et al., 2007). Findings consistent with this hypothesis show

that humans are quicker and more accurate in judging eye gaze when the sclera is depigmented compared to pigmented (Yorzinski et al., 2021). Additionally, neurotypically developing children and adults (but not children with ASD) show a preference for eye stimuli with visible white sclera (Segal et al., 2016; Wolf et al., 2023).

Eye gaze has a variety of different functions, and the “eyes can both signal and perceive” (Gobel et al., 2015, p. 359). As such, developmental theories often highlight the role of gaze as a signal for others’ attention and intention (Akhtar & Gernsbacher, 2008). Gaze can be informative for external states and direct attention to specific features in our environment (Emery, 2000; Frith, 2008; Gobel et al., 2015). Compared to other cues such as head or body orientation, the eyes are a clearer indicator of the attentional focus of another agent (Emery, 2000).

Additionally, eye gaze can signal intentions to others, like invitations to approach and engage or warnings to retreat (Frith, 2008; Gobel et al., 2015; Shepherd, 2010). Looking into another’s eyes can serve as a “window into the mind” (Shepherd, 2010, p. 10), allowing a glimpse into their beliefs and desires. Therefore, gaze can signal internal emotional and mental states (Emery, 2000), and, as such, is foundational for more complex social-cognitive abilities (Shepherd, 2010). For example, following eye gaze facilitates anticipating future actions of an agent (Friesen & Rao, 2011; Zohary et al., 2022) and enables people to learn through observation (Frith & Frith, 2007).

Eye gaze is also relevant for pragmatic and language abilities. Monitoring the eye gaze of a conversational partner enables turn-taking (Degutyte & Astell, 2021), the formation of common ground (Bohn & Köyメン, 2018; Tomasello et al., 2007), and learning new words (i.e., labels) by identifying the target object (Hernik & Broesch, 2019; Macdonald & Tatler, 2013).

In sum, eye gaze is fundamental for social interaction, communication, collaboration, and cultural and social learning (Bohn & Frank, 2019; Emery, 2000; Frith & Frith, 2012; Hessels, 2020; Moore, 2008; Rakoczy, 2022; Tomasello & Rakoczy, 2003).

### 1.2.2 Terminology

Several different concepts exist that describe an agent’s perception of another’s eye gaze (see Akhtar & Gernsbacher, 2008; Emery, 2000; Itakura, 2004). I will focus on defining *mutual gaze*, *gaze following*, *gaze alternation*, *joint attention*, and *shared attention* (arranged by (most likely) order of increasing complexity in cognitive processing and intentionality understanding).

## *1 General Introduction*

Mutual gaze describes the attention of two agents directed to each other (Emery, 2000); for example, when a child and their caregiver look at each other. As a form of dyadic gaze, it is considered a sign of social engagement (Akhtar & Gernsbacher, 2008).

Gaze following marks the process of identifying the attentional focus of another agent and turning one's gaze in the same direction (Del Bianco et al., 2019). For example, gaze following occurs when an agent observes that the others' gaze is not aimed at them and subsequently redirects their attention along the others' line of sight to a specific point in space (Emery, 2000). Some studies still refer to gaze following, even when the changes in gaze direction are confounded with simultaneous posture, head, and voice changes (Akhtar & Gernsbacher, 2008).

Gaze alternation describes switching between looking at an object and an agent's eyes and is a fundamental component of joint attention (Akhtar & Gernsbacher, 2008). Joint attention, in turn, describes an episode in which one agent (i.e., the initiator) gazes at an object, which causes another agent (i.e., the responder) to align and turn their gaze to the same object (Stephenson et al., 2021). It is similar to gaze following except that the attentional focus is directed at a specific target/object (Emery, 2000) and, as such, involves a triadic relation ("triadic connectedness," (Bard et al., 2021)) between two agents and an object (Lee et al., 1998).

A related term to joint attention is shared attention, which has been proposed to include the awareness of the common attentional state of both agents (Emery, 2000). Both individuals intentionally establish that they are looking at the same object; for example, by back-checking between the object and the other agent's gaze. However, some researchers use the terms joint and shared attention synonymously (Emery, 2000), while others argue that joint attention already encompasses the awareness and coordination of shared visual attention (e.g., Tomasello, 1995; Tomasello, 2022; Tomasello & Farrar, 1986).

The present dissertation and the included studies focus on gaze following. Gaze following is often seen as a pre-requisite and first ingredient of a joint attention episode (Moll & Meltzoff, 2011; Stephenson et al., 2021). Researchers have argued whether gaze following reflects an intentional attribution of mental states toward other agents or whether it serves as a more automatic, implicit precursor of later-developing ToM abilities (Baron-Cohen, 1995; Carlson et al., 2013; Gopnik et al., 1994). Beaudoin et al. (2020) categorized "adopting the visual perspective of another person" into the "percepts" category in a ToM classification. Moll & Meltzoff (2011) have argued that joint attention and gaze following could be seen as Level 0 perspective-taking. Regardless of whether or not

gaze following is seen as a component of ToM, it remains a central cornerstone in social cognition and a developmental precursor of many advanced forms of reasoning about others' minds.

### 1.2.3 Developmental Milestones

Children's cognitive abilities related to eye gaze evolve from sensitivity to dyadic social interactions to initiation of triadic interactions, with sensitivity to these interactions preceding their initiation, and dyadic interactions preceding triadic ones (Striano & Reid, 2006). Infants as young as three months turn their eyes in the same direction as an adult when the adult turns their head and gaze toward one of two objects (D'Entremont et al., 1997; Gredebäck et al., 2010). While this is often considered as the onset of gaze following, infants initially rely more on head than gaze direction (Lempers et al., 1977; Michel et al., 2021). Brooks & Meltzoff (2005) have consequently argued that infants begin to "view others as 'body orienters'" (p. 541) (also see Paulus et al., 2016), before they rely on eye gaze as a significant cue to others' attention.

By the age of one, gaze following becomes more sophisticated (Shepherd, 2010). For example, infants are more likely to follow gaze when the agent's eyes are open versus closed (Brooks & Meltzoff, 2002). They can use gaze (and emotional) cues to predict the next action of another agent (Phillips et al., 2002). By 14 months, gaze following is contingent on past experiences with the interaction partner's looks: When another agent had previously acted as a "reliable looker" (i.e., smiling at a container with a toy), infants were more likely to follow gaze behind a barrier than when the agent had previously acted as an "unreliable looker" (i.e., smiling at an empty container) (Chow et al., 2008). At the same age, infants interpret ostensive eye gaze and pointing as relevant communicative cues for finding a hidden toy (Behne, Carpenter, & Tomasello, 2005). By 12 to 18 months, infants follow gaze to locations outside their immediate line of sight (Butterworth & Jarrett, 1991; Corkum & Moore, 1995; Deák et al., 2000; Moll & Tomasello, 2004).

Children's abilities develop from understanding dyadic to triadic eye gaze and include responding and initiating joint attention episodes (Lee et al., 1998; Striano & Reid, 2006). However, young children might be more oriented toward objects instead of gaze itself (Masangkay et al., 1974) and use another's gaze as a cue for salient objects in their surroundings (Moore, 1999; Moore & Corkum, 1994). Consequently, the representation between the looker and target does not necessarily entail a representational understanding of mental states (Doherty et al., 2009): "Young children might

not represent gaze as gaze” (p. 298), instead they “[...] might view gazing as something similar to touching something” (p. 297).

Gaze following beyond these qualitative milestones in infancy is rarely studied. Some evidence suggests that the explicit and accurate judgment of gaze direction alone – without confounding head and/or body orientation – might emerge later in development. Children around three to four years of age only start to reliably interpret the direction of gaze when it is not directly facing them and the joint attention of others (Anderson & Doherty, 1997; Doherty & Anderson, 1999). Similarly, Doherty et al. (2009) found that most two- and three-year-olds performed below/around chance in gaze judgment tasks, while preschool children became more accurate, showing adult-like performance around six years of age. Even with congruent head and eye movements, 4.5-year-olds were only moderately accurate in identifying targets separated by 10° (Butterworth & Itakura, 2000).

In sum, gaze following emerges early in infancy and becomes more sophisticated throughout the first years of life. The explicit and accurate evaluation of eye gaze might develop later in childhood.

#### 1.2.4 Individual Differences

As with other social-cognitive abilities, variation in children’s gaze-following abilities has been documented. An individual’s ability to follow gaze has consequences for their real social life, particularly regarding social interactions and communications with others (Carpenter et al., 1998). The role of gaze following and language abilities has been highlighted by the seminal finding of Brooks & Meltzoff (2005), who showed that gaze following at ten months is predictive of children’s language abilities at 18 months. Fitting to this result, children who spent more time following an agent’s gaze to the target object showed larger vocabularies at 18 months (mediated by children’s object processing ability) (Okumura et al., 2017). Gaze following has been argued to trigger comprehension of an agent’s intentional relations to objects – “an understanding that may play a critical role in word learning (at least the learning of object labels)” (Akhtar & Gernsbacher, 2008, p. 60).

Additionally, gaze following might be related to goal and intention understanding. For example, infants’ gaze and point-following abilities in triadic interactions correlate with their ability to recognize imitation; that is, distinguishing whether another agent imitated infants or whether the same object manipulations were mechanically performed (independently of any visible actions by the other agent) (Agnetta & Rochat, 2004).

Individual differences in the emergence of gaze following might be predicted by contextual factors in children's social and emotional environment: Infants showing a secure attachment style and being raised by mothers with lower levels of maternal postpartum depression showed higher frequencies of gaze following (Astor et al., 2020).

Gaze-following research has also gained substantial traction in clinical research focusing on developmental disorders, especially in ASD (Del Bianco et al., 2019). One diagnostic criterion for ASD is an alteration in non-verbal communication, including the social use of eye contact (American Psychiatric Association, 2013). Forgeot d'Arc et al. (2017) reported that "gaze direction detection was less accurate in autism spectrum disorder than in control participants" (p. 100). Children with ASD prioritize head over pupil motion (Mihalache et al., 2020) and show reduced preferential looking times to eye and mouth regions of the face (Constantino et al., 2017). While some individuals with ASD exhibit no impairment in gaze perception, others may be less inclined to initiate eye contact and joint attention, which might influence the course of social interactions (Stephenson et al., 2021).

### **1.2.5 Cross-Cultural Research**

Few studies have assessed children's gaze-following abilities across diverse communities. One exemplary work comes from Callaghan et al. (2011) who studied 12- and 17-month-old children from rural Canada ( $n = 35$ ), Peru ( $n = 38$ ), and India ( $n = 65$ ). They examined gaze following in scenarios where an agent turned and gazed either at a toy behind a barrier (experimental condition) or a sticker in front of it (control condition) and assessed whether children crawled behind the barrier. Despite cross-cultural variation in absolute crawling rates, children across communities crawled relatively more frequently towards a barrier when an agent gazed at an object behind it rather than in front of it (Callaghan et al., 2011).

Hernik & Broesch (2019) assessed whether differences in face-to-face interaction influence gaze following (with congruent head orientation) in five- to seven-month-old infants in Vanuatu. While face-to-face interactions are less frequent in Vanuatu than in Western communities, infants showed similar gaze patterns: They followed gaze more when they were communicatively addressed beforehand (by infant-directed speech). The authors conclude that "following of gaze in communicative contexts may be available to human infants from various cultural groups regardless of the frequency of exposure to communicative gaze signals from caregivers" (Hernik & Broesch, 2019, p. 7).

## *1 General Introduction*

A recent study by Astor et al. (2022) investigated the effect of maternal postpartum depression on gaze following in 9-month-olds from Bhutan and Sweden. Infants from both countries showed similar rates of gaze following. However, a negative association between gaze following and maternal postpartum depression was only found in Swedish infants. The authors' conclude the results support the cultural mitigation hypothesis, stating that maternal postpartum depression does not have the same effect on child development across cultures and that, for example, larger interdependent family structures might serve as protecting factors.

Other cross-cultural research has focused on mutual eye gaze, joint attention, and the factors influencing these abilities. For example, cross-cultural variation has been documented in how infants are typically held, which naturally affects how likely they engage in face-to-face interactions (see study above) and thereby receive the opportunity to engage in mutual gaze (Akhtar & Gernsbacher, 2008). Kaluli mothers in Papua New Guinea tend to carry infants facing away from them, and infants and caregivers rarely look into each other's eyes (Ochs & Schieffelin, 1984). Similarly, mothers from the Gusii community in Kenya focus less on gaze and verbal interactions and more on touch than mothers from Boston, USA (Richman et al., 1992). Interestingly, Gusii mothers might use gaze aversion to calm an infant when they are excited (Dixon et al., 1981).

Childers et al. (2007) examined whether children's joint attention abilities were affected by being carried on the caregiver's back. The results suggest similar qualitative and quantitative behavioral patterns in Ngas-speaking infants in Nigeria (though notice the small sample size of 16 participants) as those found in English-speaking infants in the USA, which speaks against a potential effect of the caregivers' carrying style on joint attention (Childers et al., 2007). Moreno et al. (2021) studied children's social interaction, joint attention, and behavior regulation across three communities in Columbia. They found no between-community differences regarding joint attention. The authors concluded that this speaks for the universality of joint attention, especially given the Wayúu's distinct socioeconomic and cultural characteristics differing from the other two communities (Moreno et al., 2021). In contrast, Gavrilov et al. (2012) found that social-cultural factors (e.g., adherence to traditional values and parental education) influenced Israeli children in their initiation of joint attention. High-level interactions and a gender difference revealed that girls, particularly those from families with stronger traditional values and with highly educated parents, initiated more joint attention episodes (Gavrilov et al., 2012).

Taken together, cross-cultural studies on eye gaze are rare – especially those focusing on “literal”

gaze following without other bodily cues or target objects. The existing studies underline similarities in gaze and attention understanding across diverse cultural communities, while some results indicate variation with regards to (the frequency of) specific behaviors and the social-environmental factors influencing those.

## 1.3 Methodological Considerations

Thus far, I have highlighted human social cognition, with a focus on the fundamental ability to follow gaze. I have summarized essential milestones in child development and showcased exemplary studies focusing on individual and cross-cultural differences in these domains. Those studies on the variation between individuals and communities remain an exception: While many studies focus on average developmental trajectories in children from the Global North (Nielsen et al., 2017), studies on individual- and community-level variation are still scarce. In this section, I will argue why individual- and community-level variation in social cognition is relevant and deserves more attention. I will then discuss whether currently existing social cognition tasks are able to capture this variation. Finally, I will propose a way forward and highlight which characteristics are desirable and needed for new, innovative tasks to measure individual differences in social cognition across diverse communities.

### 1.3.1 Relevance of Individual- and Community-level Variation

Classical cognitive science assumes that human cognition is universal and invariant in its structure (Kroupin et al., 2024; Levinson, 2012). Consequently, traditional experiments often rely on small sample sizes to inform their theory and give little weight to individual differences. When developmental research questions focus on condition differences or the average age at which children pass a given social-cognitive task, variation between children is often handled by excluding outliers and calculating mean scores. As such, between-group (e.g., condition) differences are highlighted as a sign of genuine cognitive variation, while individual differences are overlooked or regarded as noise or measurement error (Amir & McAuliffe, 2020; Kidd et al., 2018). I will argue that individual and community-level variation is a valuable source of information that can help us understand the structure of social cognition and its development across diverse child-reading contexts.

## 1 General Introduction

Why should we care about individual differences? Indeed, many research questions in developmental psychology concern individual differences. A textbook example from developmental psychology is the question of (dis)continuity in development. Do children evolve like a butterfly that goes through distinct stages – from caterpillar to cocoon to butterfly? Or do they develop similarly to a tree that grows continuously over time (Parnes & Pagano, 2022, p. 8)? Two historically influential theories of cognitive development highlight the different stances. A classic example of a stage-like developmental theory is Piaget's Theory of Cognitive Development (Piaget, 1929, 1936, 1954, 1964, 1971). Piaget assumed that children progress through qualitatively different stages in a set universal order (i.e., sensorimotor, preoperational, concrete operational, formal operational), and in each stage, interpret the world differently, with increasing levels of complexity. An example of a gradual process developmental theory is Vygotsky's Sociocultural Theory (Vygotsky, 1962, 1978, 1987). Vygotsky assumed that change occurs slowly and gradually and that cognitive development is driven by an individual's social interactions and cultural context – not pre-defined by certain stages. According to this theory, social interaction shapes social cognition. To examine questions concerning the (dis)continuity in development, studies must accurately track children's individual abilities across time. While simple age effects can sometimes serve as a proxy for relevant co-occurring events in development (e.g., school entry), age is not *per se* a causal predictor (McLean & Riggs, 2022, p. 3). Consequently, individual differences studies are a powerful tool to build and test developmental theories and the structure of social cognition (Happé et al., 2017). Additionally, individual differences studies are needed to evaluate (clinical or educational) intervention programs. For example, capturing change before and after an intervention helps to examine whether children can be trained to improve their perspective-taking abilities (Lecce et al., 2014; Ruffman et al., 2018; Zhang et al., 2021).

Why should we care about variation between social, cultural, or linguistic communities? Western communities should not have a unique central place in human psychology nor should they be seen as the default, norm, or “healthy” standard (Kline et al., 2018; McLean & Riggs, 2022). Indeed, participants from the Global North or Western, Educated, Industrialized, Rich, Democratic (WEIRD) communities are likely to be outliers of the human species (Apicella et al., 2020; Henrich et al., 2010). Contrary to classical cognitive science implicitly assuming little variation across communities (Henrich et al., 2010), cross-cultural research can assess how ecological and cultural environments form and shape human cognition. “After all, there is no ecology- or culture-free human” (Amir & McAuliffe, 2020, p. 431). Developmental psychology might especially benefit from a cross-cultural perspective

and vice versa: Early childhood is a period of especially sensitive and plastic brain growth, in which children are first fully exposed to ecological and cultural inputs (Haun, 2015). Studying developmental pathways in different communities will allow us to (1) establish a “globally representative developmental science” (Broesch et al., 2023, p. 589), (2) rigorously test the generalizability of theories and their underlying assumptions that were originally developed in one particular culture, (3) explore the universality or variability of (social) cognition, and (4) examine how children’s early life experiences structure their core cognitive abilities (Amir & McAuliffe, 2020; Apicella et al., 2020; Broesch et al., 2023; Hughes et al., 2014; Liebal & Haun, 2018; Selcuk et al., 2023).

Why should we combine efforts to study individual and cross-cultural variation? Studying group effects of culture on cognition does not suffice: Any given community consists of a group of individuals. Vogeley & Roepstorff (2009) stated that “Culture is not a well-defined rigid body of rules that shapes each and every individual of a given culture in a similar, uniform way; instead, it dynamically and continuously interacts with its constituting individuals” (p. 512) and as such, “culture needs to be considered as a dynamical system of individuals” (p. 511). Participating in culture transforms individuals, and participation of individuals transforms culture itself (Rogoff, 2003). Environmental and cultural factors – on a macro, community level and a micro, family level – interact with children’s unique developmental trajectories and outcomes (Broesch et al., 2023). While aggregated measures of experience and cognition may cluster within communities, an individual’s developmental trajectory may point in different directions than a group-level comparison (Amir & McAuliffe, 2020; Bohn, Fong, et al., 2024; Ilgaz et al., 2022). Between-community differences are restricted in their ability to explain how individuals vary in their behaviors throughout the lifespan. They can hardly describe why, how, and which cultural factors shape it (Amir & McAuliffe, 2020). Cultural factors can cause psychological and behavioral variation in developmental processes both within and across communities (Kline et al., 2018), and indeed, within-group variation often outweighs between-group variation (Amir & McAuliffe, 2020). Consequently, we need to measure and link children’s cognitive development and their daily experiences (i.e., how a child perceives their everyday cultural and ecological environments) on an individual level across different communities (Bohn, Fong, et al., 2024; Gutchess & Rajaram, 2023).

In sum, the need for an individual differences perspective on child development is more than evident. Studying individuals from diverse social, cultural, and linguistic communities will broaden the scope with which we can capture children’s living conditions and developmental pathways (Bohn, Fong, et al., 2024). Ultimately, the flexibility of mechanisms in human development and the resulting

variation in psychological and behavioral outcomes is “a feature rather than a bug” (Kline et al., 2018, p. 5).

### 1.3.2 Terminology

Before I consider the current state of existing social cognition tasks, I will clarify some relevant terms in this context. First, *variability* and *variation* are important when describing individual differences. The definitions of variability and variation greatly resemble each other according to the *APA Dictionary of Psychology* (American Psychological Association, n.d.-d, n.d.-e). Both terms focus on differences between individuals that can be applied to the behavioral level. As in most developmental literature, the terms variability and variation will be used interchangeably in this work.

The psychometric properties of a task are often assessed by considering its *validity* and *reliability*. *Validity* concerns the truthfulness of a task or the degree to which a task captures what it is designed to measure conceptually (American Psychological Association, n.d.-c). There are several different types of validity. In the context of this work, we focus on *convergent* validity (i.e., the degree to which two tasks that should be theoretically related are indeed related), *predictive* validity (i.e., the degree to which a task relates to other tasks separated by a determined period (= predicting scores in the other task)), and *external* validity (i.e., the degree to which the results of a task can be generalized beyond the original sample). *Reliability* refers to the degree to which a task produces consistent, stable results when repeated again or the degree to which a task is free of random measurement error (American Psychological Association, n.d.-b). Two main types of reliability are often assessed when evaluating a given task. *Internal consistency* focuses on the relationship between items in the same task to ensure they measure the same construct. (*Test-*) *Retest reliability* assesses a task’s stability over time and estimates the relationship of the task scores on two different administration occasions (e.g., test day one followed by test day two, three weeks later).

### 1.3.3 Existing Social Cognition Tasks

As I have argued, many fundamental research questions in developmental psychology are interested in, or build upon, individual differences. I want to start considering whether existing social cognition and ToM tasks are capable of measuring individual differences by reviewing one exemplary

study. Longitudinal work by Sodian et al. (2016) investigated how goals, beliefs, and desires relate to moral ToM. They reported that “contrary to expectations, neither goal encoding nor implicit false belief understanding was correlated with the Mo[ral] ToM false belief question” (p. 1227). Two main interpretations of these results come to mind. First, the researchers’ hypothesis could simply be incorrect: Potentially, goal encoding and implicit FB understanding are not related to moral ToM. Alternatively, and more optimistically, the non-existent relationship could be explained by methodological issues. Following this interpretation, the applied tasks could not accurately capture variation between children and, therefore, did not find a relationship between the variables. Interestingly, Sodian et al. (2016) stated two sentences later: “[...] verbal IQ was positively correlated with almost all the assessed variables” (p. 1227). What could this finding hint at? The task for verbal IQ was – by definition – designed to capture individual differences in linguistic intelligence. However, tasks used for correlational analyses need to leave room for individual differences in order to find and correlate them (Siegelman et al., 2017).

A classical developmental study paradigm “involves describing a social scenario, sometimes using cartoons or puppets, and then asking test questions about what the protagonists feel, want, or know, or what they will do next” (Slaughter, 2015, p. 170). Often, they present children with two objects. For example, the Sally-Anne FB task lets children witness how a ball gets moved from a box to a basket while another agent does or does not witness the change of location (Baron-Cohen et al., 1985; Wimmer & Perner, 1983). Children then get asked where the agent believes the ball to be. Possible responses are (1) the box or (2) the basket. Similarly, in the traditional gaze-following paradigm (e.g., Astor et al., 2020; Byers-Heinlein et al., 2021; Gredebäck et al., 2010; Ishikawa et al., 2022), an agent gazes at a location or toy to her left- or right-hand side. The study outcome measures children’s reaching behavior toward the two toys (or, in more recent studies, children’s looking times). What becomes apparent is that these common social cognition tasks rely on dichotomous designs: An object is either on the left- or right-hand side and a child can either pass or fail the task. Finally, average scores are calculated, for example, the group-level mean in performance. Often, social cognition measures rely on only one or two trials (Cutting & Dunn, 1999; Henry et al., 2016). All these characteristics lead to poor measurement accuracy and little sensitivity to individual differences (Beaudoin et al., 2020). An inadequate assessment of an individual’s (social) cognition can mask connections between cognitive processes and their underlying factors and overshadow developmental trajectories (McLean & Riggs, 2022; Petersen, 2023).

To briefly summarize: To assess the (inter)dependence of two cognitive abilities or environmental

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factors, an individual's score must be measured accurately on both scales. Indeed, the correlation between two tasks cannot be greater than the reliability of each individual task (DeVellis, 2006). In light of this statistical feature, the psychometric properties, especially the validity and reliability of measures, gain importance.

In the last ten years, a handful of articles have reviewed social cognition tasks with regard to their measurement properties. For example, Ziatabar Ahmadi et al. (2015) conducted a systematic review of comprehensive ToM measures for preschool children. Exclusion criteria were single tasks such as the classical FB task and/or no description of the measure's structure, validity, and reliability. From the originally found 1,237 articles, only eleven measures fulfilled all criteria and were included in the review. Of these eleven measures, six relied on verbal measures, two on a forced choice, and three were filled in by children's caregivers. Only one measure was computerized. All eleven measures were judged to be of moderate or high quality. Yet even within this set, it was rare that validity (e.g., content, construct, criterion-related, or discriminant validity), test-retest reliability, and internal consistency were all reported.

Another systematic review by Beaudoin et al. (2020) focused on ToM measures (including single tasks) for children aged 0 to 5 years of age. The authors argued that despite much progress has been made to study children's ToM understanding, drawing robust conclusions about (a)typical development remains challenging – mainly because of methodological issues. According to their analysis, social cognition studies rarely report psychometrical information: Less than one-fifth of the identified 220 measures had information on their internal consistency, less than one-tenth provided test-retest reliability estimates, and shockingly, even fewer measures had examined the construct validity. More than two-thirds of the study samples solely relied on English-speaking participants, and the majority of measures focused on belief understanding (Beaudoin et al., 2020).

The most recent review by Fu et al. (2023) systematically listed existing ToM tasks for children from 0 to 12 years and categorized them by the captured dimension (cognitive vs. affective, inter- vs. intrapersonal), construct (e.g., knowledge access, diverse beliefs, first-order FB), presentation mode (e.g., spoken stories, cartoons, picture sequences, interviews), response mode (e.g., spoken language, multiple choices in words/pictures/objects, actions), underlying test theory (classical test theory vs. Item Response Theory (IRT)), and psychometric properties. Similarly to Beaudoin et al. (2020), Fu et al. (2023) highlighted the over-reliance on tasks measuring children's FB understanding. Furthermore, only one-fifth of the 127 included ToM tasks reported at least one reliability or validity

estimate.

Measures that validly and reliably assess the development of social cognition cross-culturally remain even scarcer (Quesque et al., 2022; Salhi et al., 2023; Waschl & Chen, 2022). It has been proposed that due to a lack of culturally appropriate tools, social cognition is one of the most challenging cognitive domains to study in diverse communities (Bourdage et al., 2023; Franzen et al., 2021).

In a systematic review, Bourdage et al. (2023) identified cross-cultural social cognition tasks for adult samples, with a focus on participants from the Global South. Of the 84 included studies, 45 focused on ToM, and six on general social cognition tasks. Thirty-one tasks were translations, 27 adaptations, 14 cross-cultural assessments, and 12 especially assembled for Global South populations. The authors classified 35 as having low quality, 27 as moderate quality, and 22 as high quality. Measurement quality often suffered under limited validity and reliability assessment and small sample sizes.

While the exact number of identified tasks vary between systematic reviews and depends on their search and inclusion criteria, the overall picture is clear: Developmental social cognition tasks suffer from unknown, underdeveloped, or inadequate psychometric properties (e.g., Hiller et al., 2014; Hutchins et al., 2008; Mayes et al., 1996). While a vast variety of social cognition and ToM tasks exist, few are designed to capture individual-level variation, let alone variation between diverse communities. As Hruschka (2020) stated, “We have a long road ahead of us in how we measure the world” (p. 458).

### 1.3.4 A Potential Way Forward

*What* psychological research questions we study and *which* communities and individuals we sample might be equally important to *how* or *with what* we measure the psychological construct in question (Barrett, 2020a; Hruschka, 2020). While the development of new tasks can be time-consuming and cumbersome, a historical perspective on science underlines that this endeavor is nevertheless worthwhile. For instance, the invention of the telescope in the early 17th century revolutionized the field of astronomy by enabling detailed observations of celestial bodies. Galileo Galilei’s observations of the uneven surface of the Moon, sunspots, the phases of Venus, and Jupiter’s moons challenged the prevailing geocentric model. They provided the first empirical evidence that the Earth and other planets revolve around the Sun. As this example illustrates, methodological advancements not only

increase measurement accuracy but can lead to significant shifts in scientific thought and knowledge.

In the research area of social cognition and/or gaze following, many researchers study (the emergence of) these social-cognitive abilities – and yet their work often revolves around similar study designs. New research questions or “groundbreaking” theories remain rare. Astor & Gredebäck (2022) postulated that “Despite a steady stream of publications on the development of gaze following, we would like to argue that scientific progress within the field is slow—that data is produced with a high frequency but without adding substantial advancements to our understanding of the phenomenon under investigation and its long-term development” (p. 192). Methodological evolution could be seen as a promising tool, as “methods can erase variation as well as capture it” (Broesch et al., 2023, p. 593). A focus on individual- and community-level variation could stimulate the gaze-following literature, challenge existing theories, and open up new research avenues. As Smaldino (2019) put it: “If we can’t reliably measure something, it’s hard to build a theory about it. [...] Better methods will help us get the right answers; models and measurements will ensure we ask the right questions” (p. 9).

What characteristics would a new task need to capture individual variation in social cognition? Objective, standardized tasks should be the goal to make a quantitative comparison between individuals possible (Schaafsma et al., 2015). As we have seen, a classical developmental research question concerns whether child development happens in stages or in a continuous way (Parnes & Pagano, 2022). To answer this (dis)continuity question, we need continuous, as opposed to dichotomous, (1) experimental manipulations and (2) outcome measures (Beaudoin et al., 2020). A continuous experimental manipulation could include several levels of trial/item difficulty and, for example, depict gradual mental states (e.g., differing degrees of knowledge or perceptual access). This might help to move beyond studying the age of first emergence and capture more qualitative differences in social-cognitive development (Slaughter & Repacholi, 2003). A continuous outcome measure could, for example, include reaction times, looking behavior, or accuracy in fine-grained action responses. This would have several advantages. First, continuous outcome measures leave room for individuals to vary (Hutchins et al., 2008; Schaafsma et al., 2015). Second, it could prevent floor- and ceiling effects in which a considerable percentage of participants cluster around the minimum or maximum available scores. Third, this might, in turn, enable sampling older children and adults to get a more complete picture of social-cognitive development across the lifespan (Hutchins et al., 2008; Slaughter & Repacholi, 2003).

Importantly, a task's psychometric properties must be examined to test whether variation between participants is genuine or due to arbitrary external factors (i.e., noise). Robust methods would show satisfactory validity and reliability estimates (Beaudoin et al., 2020; Fu et al., 2023). Presenting more than one trial per child (or, in the best case, as many as possible) would increase the precision with which we can estimate a participant's ability level (Siegelman et al., 2017). Additionally, the task could capture more possible response patterns which leads to a better differentiation between individuals. Simultaneously, task duration should be brief to allow large sample sizes (especially important for individual difference studies) (Molleman et al., 2019).

Regarding the construct(s) that a task measures, researchers have argued for including more diverse mental states and not falling into the common pitfall of only testing for FB understanding (Beaudoin et al., 2020; Fu et al., 2023; Heise, 2023; Hiller et al., 2014). When designing new tasks, processing demands need to be kept in mind so that children's social-cognitive abilities are not masked by extraneous factors (Setoh et al., 2016). Artificial experimental setups with academic test questions should be avoided as they might lead to potential pragmatic confusion (Oktay-Gür & Rakoczy, 2017; Rakoczy & Oktay-Gür, 2020). Instead, new tasks should aim to measure how children genuinely apply social cognition within contexts that resemble everyday life situations (Slaughter & Repacholi, 2003). Fu et al. (2023) recommended that ToM tasks should include visual stimuli, such as pictures or videos, and response formats with little language demands to aid children's task understanding and language processing.

For studying the variability or universality of our core social-cognitive abilities across communities, studies need to stop oversampling participants from the Global North and include more diverse communities (Arnett, 2008; Henrich et al., 2010; Kline et al., 2018; Krys et al., 2024; Lillard, 1998). To include more communities, tasks must be adaptable to different languages and superficial stimulus appearances (Bourdage et al., 2023). Furthermore, reliability and validity estimates of a task should be verified in every community as these psychometric properties cannot be generalized from one community to another (Bourdage et al., 2023; Hajdúk et al., 2020; Waschl & Chen, 2022). While non-verbal tasks avoid issues of inaccuracies in translation, all stimuli and methods should be assessed as to whether they map to the same psychological constructs, are relevant to the participants of the studied community, and get interpreted in similar ways across communities (Kline et al., 2018).

Amir & McAuliffe (2020) have argued for combining cross-cultural and individual differences work with formal modeling. Formal modeling acts as a promising tool to explain and predict the scale,

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patterns, and sources of variation in human behavior and reverse-engineer the computational cognitive processes causing them (Amir & McAuliffe, 2020; Simmering et al., 2010). This might also help solve the issue that researchers often interpret uniform behavior as evidence for a universal cognitive mechanism, and behavioral differences as evidence for cultural influences and lack of universality – without explaining how and which factors generate the psychological and/or behavioral differences (Kline et al., 2018). For example, behavioral outcomes might vary in their developmental timing and yet rely on the same universal mechanisms (Broesch et al., 2023). Formal models will help to define these underlying cognitive processes. In addition, formal modeling forces researchers to explicitly state assumptions underlying their theories, which leads to testable and novel hypotheses – ultimately leading to better theories (Simmering et al., 2010; Smaldino, 2019). Studies capturing systematic differences in behavioral outcomes will help us to evaluate a model’s predictions (Amir & McAuliffe, 2020). Therefore, models benefit from accurate, reliable, and replicable measures on an individual level (Smaldino, 2019).

Methodological advancements do not lead anywhere if they are not shared within the scientific community. Elson et al. (2023) have argued that psychological tasks are often used only a handful of times – by the same researcher(s) who designed the task. The reluctance to share one’s own tasks and re-use tasks of other researchers hinders cumulative science. As the authors figuratively pointed out, “psychological measures aren’t toothbrushes” (Elson et al., 2023, p. 1). Therefore, Elson and colleagues call for more transparency and standardization in the psychological tasks we implement and apply. Open science principles will help other researchers to reproduce study results, test their generalizability, and eventually address issues related to the replicability crisis in (developmental) psychology (Open Science Collaboration, 2015; Schimmelpfennig et al., 2024; Sen & Gredebäck, 2024; Syed, 2021).

As I have argued, the field of developmental psychology would benefit from establishing new tasks to capture individual- and community-level variability in social cognition. The present dissertation aims to implement this paradigm shift and showcases an example of how methodological advancement in the area of social cognition – more specifically, gaze following – might be possible. In the following chapter, I will outline the aims and approaches of the four studies included in this dissertation in greater detail.

## **2 General Approach**

### **2.1 Aims of this Dissertation**

The overarching aim of this dissertation is to deepen our understanding of variability in a core social-cognitive ability, namely gaze following. First, I have highlighted calls for better (i.e., valid, reliable, generalizable) social cognition tasks. The projects included in this dissertation show an exemplary way how to close this methodological research gap in the future and try to demonstrate that, even if demanding, methodological advancement is feasible and fruitful. Second, applying the newly designed gaze-following task, I hope to show how cross-cultural individual differences research on social cognition helps us to answer fundamental questions about the development, cognitive processes, and universality of humans' extraordinary social-cognitive abilities. In the following, I will outline the role each of the four included studies plays in reaching these overall objectives.

#### **2.1.1 Aims of Study I**

To relate cognitive abilities and external factors to each other, social cognition tasks need to be able to measure individual differences. Tasks that are designed to do so remain rare. This study aimed to approach this issue and described the development and validation of our new gaze-following task, the Task for Assessing iNdividual differences in Gaze understanding-Open (TANGO). We have designed a playful study in which participants are asked to locate a balloon. The twist is that the participants cannot see the balloon itself. However, they see how another agent (i.e., pig, monkey, sheep) gazes out of a window, toward the balloon. Participants have to follow the agent's gaze to locate the balloon. We designed two task versions: (1) a discrete version in which the balloon was hidden inside a box, and (2) a continuous version in which the balloon was hidden behind a hedge. The box version was generically created in a way that enabled different numbers of boxes (min. 2, max. 8). Participants' gaze-following abilities were measured dichotomously (correct/incorrect) in the discrete box version and continuously in the hedge version (distance between the actual target's location and the participant's estimated location).

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Study I consisted of three main parts. In the first part, we assessed the task's usability in a sample of 3- to 5-year-old children and adults. Children came from Leipzig, Germany, and either completed the study in their kindergartens in a quiet room or remotely at home, with the help of their caregivers. Adults were sampled internationally via a participant recruitment platform and completed the study remotely online. Participants completed the TANGO in its discrete box version with 5 (for children) or 8 boxes (for adults) or the continuous hedge version. We assessed whether the TANGO captured individual differences and whether data collection mode (i.e., remotely vs. in-person) influenced children's performance. In the second part, we aimed to assess whether these individual differences were reliable. We repeated data collection two weeks after the initial session and estimated retest-reliability and internal consistency. In the third part, we attempted to measure the validity of the TANGO: For its construct validity, we explored the relationship between the TANGO and variables of children's daily social environment, and for its predictive validity, the TANGO's relationship with a language task six months later. Together, these studies aimed at thoroughly assessing the TANGO as a new task to measure individual differences in gaze following.

### **2.1.2 Aims of Study II**

Study II built upon the results of Study I and adopted the TANGO to examine three research questions related to individual differences. We aimed to assess (1) how gaze following develops across the lifespan, (2) how people cognitively process gaze cues, and (3) how gaze following relates to other (social-) cognitive abilities.

To answer the first question, we remotely collected data from 3- to 80-year-olds and examined changes in their ability to follow gaze. While previous gaze-following research often focused at the youngest age in which children can follow gaze (e.g., D'Entremont et al., 1997; D'Entremont, 2000), we focused on the development (in precision) after this initial milestone. As in Study I, children participating in the study lived in Leipzig, Germany, and either completed the study online or in their kindergartens. Adults were internationally sampled and remotely participated in the study online.

Second, we developed a computational cognitive model to explain the underlying processes of how people process gaze. We hypothesized that participants observe the pupil location within the eye and calculate gaze vectors that point toward the attentional focus. As this process was likely to be noisy, individual differences were assumed in the participant's uncertainty surrounding this gaze

vector. We judged the evidence for this gaze model by comparing it to two alternative explanations of the data: a center bias and a random guessing model. Due to its underlying geometrical features, the gaze model predicted that uncertainties around the gaze vector increased the further an agent looked to the side. We planned to check for this signature pattern in the data by assessing the participants' imprecision levels in gaze following across different target positions.

Third, we aimed to test whether an individual's precision in gaze following related to other (social-) cognitive abilities. Consistent with our gaze model, we assessed whether gaze following was related to non-social vector following. To test this claim, we designed a new vector following task that matched the TANGO as closely as possible but within a non-social context. The vector following task relied on the concept of magnetism and asked children to locate a magnet based on the location of a gearwheel. Furthermore, we applied four tasks from a ToM task battery (Wellman et al., 2001) and two perspective-taking tasks (Flavell, Everett, et al., 1981; Flavell, Flavell, et al., 1981). These comparisons aimed to disentangle the components that make up gaze following. In sum, Study II aimed to provide a comprehensive picture of the lifelong development, cognitive processes, and components of gaze following.

### **2.1.3 Aims of Study III**

Studies I and II presented above relied on child samples from the Global North (Leipzig, Germany). Traditional developmental theories often assume that central features of social cognition hold universally true across human cultures (Wellman, 2013). On the other hand, communities vary in how infants are typically carried and how often they interact face-to-face (see introduction), and thus, we might expect cross-cultural differences in how children determine another's attention and follow gaze (Akhtar & Gernsbacher, 2008). With Study III, we aimed at evaluating the universality and variability of gaze following. To broaden our perspective, we collected data of children's gaze-following abilities from 17 diverse communities spanning five different continents. To our knowledge, this attempt constituted the largest international sample on children's gaze-following abilities to this date. For further information on the studied communities, the sample selection, and participant recruitment strategies, please see the online supplements of Study III (accessible under <https://github.com/ccp-eva/gafo-cc-analysis/blob/main/supplement/supplement.pdf>).

We aimed to analyze the data in three different ways. First, we examined the developmental trajectory of gaze following across communities. Second, we explored whether absolute differences

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in gaze-following imprecision related to variables concerning the data collection mode and/or children's daily environments. Third, we checked whether the signature pattern predicted by our gaze model in Study II could be found in all communities studied. With this approach, we aimed to investigate whether the same underlying model could describe how children worldwide process gaze. All in one, this study intended to provide first evidence for the universality or variability of gaze following across diverse communities.

### **2.1.4 Aims of Study IV**

Study IV intended to strengthen the basis for using the newly developed gaze-following task in cross-cultural research. The paper had three main aims. First, we described the process of designing the cross-cultural gaze-following task, the TANGO-Cross-Cultural (TANGO-CC). We aimed to provide a roadmap for other researchers on how to pragmatically develop a new social cognition task that can be used for studying diverse communities.

Second, we provided a tutorial how other researchers can use and customize the TANGO-CC according to their needs. This section aimed to highlight the components of the task that are constant and those that are variable and can be adapted to diverse languages and communities.

Third (and most importantly), we aimed to examine the TANGO-CC's reliability across diverse communities. While the psychometric properties of the TANGO were previously tested in one setting (Leipzig, Germany; Study I), we cannot simply generalize these findings and assume the task's validity and reliability based on a mono-cultural sample. For this purpose, we aimed to further analyze the data set from Study III. We assessed performance across trial types, within- and between-community variation, and internal consistency measures in all 17 communities studied. Together, this study aimed at providing a direction of how researchers can study variation in social cognition at an individual- and community-level.

## **2.2 Research Practices**

In the sections above, I have highlighted the theoretical approaches and aims of the publications included in this dissertation. All of these studies build upon the same underlying testing infrastructure.

As this dissertation strongly focuses on methods development, I want to outline our main methodological decisions in designing this new testing infrastructure. In-depth information regarding each specific study can be found in the corresponding manuscripts in Appendix A.

### 2.2.1 Presentation Mode

Before designing the TANGO, we had to choose a presentation mode for the experimental stimuli. Many traditional developmental studies have designed interactive tasks in which an experimenter or caregiver engages with the child. This makes standardization difficult as experimenters (or caregivers) have individual communication styles, might accidentally alter the instruction script due to memory gaps, or need replacement at some point (e.g., when temporary work contracts of research assistants end). In addition, this approach makes scaling data collection difficult as training experimenters requires substantial temporal and financial resources. Since studies investigating individual differences rely on large sample sizes, we decided to take another route. We designed an online testing platform that hosts studies in all common web browsers. It can be accessed on all devices (e.g., laptop, tablet) and does not require prior installation. Even though the task was programmed as a website, it does not require an internet connection (for more information, see programming framework further down). The task itself is presented as an animated, interactive picture book. Audio instructions guide children through the task and describe the presented events. Trial types build up on each other and familiarize children with the response format (i.e., clicking or touching the screen).

The design as an online study has several advantages. First, it allows for maximally standardized procedures as audio instructions are pre-recorded and automated. Second, data does not need to be entered manually or coded from video. Instead, the website stores response times and participants' clicking behavior automatically. This greatly reduces potential coding biases and rater errors. Third, the presentation as a website allows for in-person and remote study participation. Families can choose whether they want to participate by coming to the research lab, or kindergartens, or whether they want to participate within the comfort of their own home. In this case, no appointments or rooms in the lab need to be scheduled. The families receive a personalized invitation link and can access the online study whenever and wherever it suits them best. This increases the inclusiveness for families with busy schedules, longer traveling distances to the lab or children who might be too shy to interact with strangers. While studies conducted in a research lab might be prone to

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over-study families with certain characteristics (e.g., families living closer by, having a higher SES or more free time), online studies might make study participation more accessible for a wider range of families – which, in turn, would increase the representativeness of the sample.

We have consciously chosen to implement an active behavioral task to circumvent issues in interpretability of implicit tasks. For example, it is unclear whether looking time measures capture children's level of surprise, attention, memory formation, or other cognitive processes, and whether they show convergent validity (Aslin, 2007; Dörrenberg et al., 2018). While our outcome response does not directly measure underlying cognitive processes, it focuses on children's active behavior, which might translate more directly into their actions in daily life.

### **2.2.2 Programming Framework**

The online study was implemented in JavaScript (client-side functionality of the website), HTML (content), CSS (styling), and PHP (server-side functionality). Since web development is a fast-moving domain, we decided against libraries such as React or full-stack frameworks such as Next.js, as projects relying on frameworks often require regular monitoring. One of our goals was to create a resilient code base with minimal external dependencies to avoid breaking changes through library or framework updates. Additionally, we aimed to keep the code base as easily accessible as possible so that researchers with less programming experience could also read through and adjust the code to their needs. First and foremost, we relied on “Vanilla JavaScript” (i.e., JavaScript without a special syntax or compile step). Furthermore, a module bundler, namely Parcel (<https://parceljs.org>) and, in later projects, Webpack (<https://webpack.js.org>), tracked modules and dependencies, optimized website performance and increased the overall developer experience (e.g., by enabling a development server and hot reloading).

For animation of visual stimuli, we used GreenSock Animation Platform (GSAP), an industry-standard, high-performance animation library (<https://gsap.com>). GSAP is widely spread in front-end development, well documented, and easy to read so including this library increased user friendliness. Stimuli were embedded as Scalable Vector Graphics (SVG), an XML format that describes elements in mathematical formulas. Unlike other binary image formats (e.g., JPG, PNG), SVG exposes its structure in plain text allowing developers to manipulate and animate individual content in real time. This greatly facilitates stimulus adjustments, such as recalculating positions of objects, and adding stimuli to the composition. SVGs ensure high resolution, consistent aspect

ratios, and relative object positioning across different view ports, which is especially important for remote data collection where participants use different presentation devices.

During website development, we used the development server made available by the module bundler. This means we could test the website on our local computer and only uploaded content to the web server once the website was fully implemented. The bundler builds an output folder (in our case called “dist”) that contains all website content in a compressed and optimized format. This folder is essential for both online and offline data collection. For online data collection, the dist folder gets uploaded to the web server, and the study can be accessed under its corresponding URL. For offline data collection, a live server can be installed which then hosts the dist folder locally. This is especially practical in settings with unreliable or non-existent internet connection: Data collection in communities living in remote villages becomes viable. Additionally, this approach is helpful for data collection with children in (German) kindergartens as these institutions often do not have public internet connection or stable telephone reception for mobile data.

URL query parameters were used to create individualized links for participating families. This way, we could pass on information from our participant database to the study website (e.g., age of the children, language of the study, personalized gift vouchers for study compensation).

### 2.2.3 Data Processing

After a child completes the task, the website automatically saves all responses and response times. The website stores all click data and, if desired, some additional device information (e.g., touch screen yes/no, what type and version of web browser) in a text format. During the initial development and the first published article (see Study I and Study II), we used JSON (JavaScript Object Notation) files commonly used for transmitting data in web applications. In later stages of the project (see Study III and Study IV), we instead used CSV (Comma-Separated Values) files as these are more commonly used among psychology researchers. In these text files, each trial is represented by one row of data. Columns depict the collected variables; for example, subject id, trial type, target location, and response. If requested, a webcam recording can be captured that films the study participation via the front camera. We implemented this feature especially for remote data collection. If caregivers consented to the webcam use, we could use the webcam recordings to ensure that indeed the children themselves carried out the task and did not get any external help. Depending on the choice of the experimenter and the data collection setup, data could be uploaded to secure servers located within

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the Max Planck Institute for Evolutionary Anthropology, Leipzig, Germany, or could be downloaded to the testing device (e.g., tablet or computer).

Data pre-processing was greatly simplified as the study data did not require any further response coding. Individual subject files were merged into one final data set using the programming language R. Data visualization and statistical analyses were conducted within the same program.

### **2.2.4 Accessibility of Study Materials**

We strongly adhered to Open Science principles in the construction of the TANGO(-CC). The tasks can be used for free via the websites (TANGO: <https://ccp-odc.eva.mpg.de/tango-demo/> and TANGO-CC: <https://ccp-odc.eva.mpg.de/tango-cc/>). This dissertation and its included publications have published all related information in online repositories on GitHub and the Open Science Framework (links leading to specific projects can be found in the respective manuscripts in the Appendix A). By cloning the corresponding GitHub repository, motivated researchers can modify and further develop the task to their needs. Furthermore, we pre-registered studies with their planned sample sizes, study procedures and analyses for hypothesis testing before data collection, and shared the study materials, analysis scripts and data sets after data collection.

Articles were written in R Markdown which allowed us to combine continuous text and results of statistical analyses into one coherent document. The aim was to reduce the chances to accidentally copy-paste incorrect or outdated findings into the manuscript. We tracked all analysis scripts and the manuscript texts in a version-controlled manner. This enables other researchers to transparently retrace decisions and changes along the way.

As the final project, Study IV incorporated refinements that have further optimized the usability of the TANGO-CC. While adapting the source code for cross-cultural stimulus presentation, I have refactored the code base; that is, I have improved the internal structure, readability, and maintainability of the software without altering its behavior or functionality. I have added comments to the code base using JSDoc (<https://jsdoc.app>), a markup language developed to document and annotate JavaScript source code files. Furthermore, I have collected frequently asked questions and created a manual for other researchers using the task (<https://ccp-odc.eva.mpg.de/tango-cc/manual.html>). Compared to the first version of the TANGO, these changes served to improve the task's sustainability over time.

# 3 General Discussion

## 3.1 Summary of Results

### 3.1.1 Results of Study I

In Study I, we have examined the TANGO as a viable task for studying individual differences in gaze following in children and adults from the Global North.

First, we found the TANGO to be engaging for all age groups. Participants could complete 15 test trials within five to ten minutes. The presentation as a web app functioned smoothly across different browsers and devices, and data was reliably uploaded to the web servers. Children showed similar developmental trajectories in both versions of the task (i.e., discrete box and continuous hedge version). While the average three-year-olds were still rather imprecise in locating the target – in the box version, only slightly better than chance – children became more precise with increasing age. In neither of the versions did the children or adults reach ceiling levels in their performance. We found individual differences across all ages. For example, some of the five-year-old children were more imprecise in their gaze-following abilities than the average three-year-old. Data collected remotely without supervision closely resembled those that were collected in person.

Second, excellent psychometric properties underscored that the individual differences captured by the TANGO were meaningful and could not be ascribed to random noise: High retest reliability estimates proved that the TANGO did not simply capture daily fluctuations but stable ability levels across time. Age-independent Generalized Linear Mixed Model (GLMM)-based estimates (Rouder & Haaf, 2019) were higher than the previously estimated *Pearson* correlations. Internal consistency estimates also pointed to the reliability of the TANGO and suggested that participants' performance within one session was not affected by trivial effects such as exhaustion or habituation. We found that different splitting and stratification methods previously proposed by Pronk et al. (2022) led to similar or even higher internal consistency estimates.

Third, the construct and predictive validity of the TANGO were established by probing correlations between gaze following and concepts considered to be theoretically associated: social interactions

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and language abilities. Children who entered daycare at a comparably older age than their peers were more likely to be imprecise in gaze following. Although the other social interaction proxies (e.g., number and age of siblings) did not improve the model fit, the results pointed in the expected direction: The more opportunities for social interactions a child had, the more precise they were in gaze following. Additionally, the TANGO was predictive of children's receptive vocabulary, as measured by the open Receptive Vocabulary task (oREV) (Bohn, Prein, et al., 2024) six months later, even when correcting for age.

Taken together, Study I established the TANGO as a reliable and valid measure of individual differences in gaze following.

#### **3.1.2 Results of Study II**

Study II showed an exemplary way in which the TANGO (in its continuous version) can be used to answer research questions on individual differences in gaze following.

First, we found that precision in gaze following develops throughout the lifespan. Childhood was characterized by rapid changes and children reached adult-like imprecision levels in gaze following at around ten years of age. During early adulthood, participants were most precise in their gaze-following abilities, and toward older age, precision levels slightly decreased again. Individuals differed from each other in all age groups.

Second, a cognitive model was designed to interpret individual differences in gaze following in a psychologically meaningful way. The proposed process model aimed to depict how participants infer the agent's attentional focus in the TANGO. It assumed that participants estimate the centers of the agent's eyeball and pupil and connect those as a gaze vector (i.e., line-of-sight). The angle between this gaze vector and a vector pointing horizontally to the ground is defined as the pupil angle. Participants were assumed to integrate the information of the pupil angles (and gaze vectors) from the left and right eye. The point at which both gaze vectors meet defines the attentional focus of the agent. Estimating the pupil angles was assumed to be a noisy process. This was modeled as participants sampling estimated pupil angles from a probability distribution, which was shaped by multiplying two Normal distributions centered on the true pupil angles with equal variance. Individual differences were modeled by differing degrees of uncertainty around the pupil angle (i.e., the variance representing the width of the distribution). The development (or refinement) of gaze

following was conceptualized as a decrease in uncertainty around the pupil angles, which would result in less imprecision in the TANGO. The characteristics of the probability distribution described above resulted in the following prediction: When the agent gazed towards the side, the distribution from which the participants sampled was wider compared to when the agent gazed centrally to the ground (see Figure 2 in Study II). Therefore, participants should be more imprecise when targets land further out.

The results provided substantial evidence for the proposed gaze model. In the child as well as the adult sample, the gaze model estimates correlated strongly with the data mean. Participants' imprecision levels across target bins resembled a U-shape, which matched the prediction of the gaze model: Targets on the very left- or right-hand side led to the highest imprecision levels, while center targets led to a decrease in imprecision. Compared to two alternative models that explained the data by a center bias or random guessing, the gaze model was clearly favored.

As became evident, the gaze model described gaze following as a social form of vector following. We tested this proposed relationship experimentally and found that gaze following correlated moderately with a non-social vector following task. Additionally, gaze following was related to two perspective-taking tasks (Flavell, Everett, et al., 1981; Flavell, Flavell, et al., 1981) but not with other ToM tasks (Wellman et al., 2001). This suggests that gaze following comprises estimations of vectors in space and evaluating another person's point of view.

In sum, Study II illustrated the continuing development of accurately interpreting another's gaze direction, along with the cognitive processes behind this ability.

### 3.1.3 Results of Study III

Developmental theories often (implicitly) assume that social-cognitive abilities develop and function similarly across human cultures. In Study III, we experimentally tested this claim.

First, we found that children in all 17 communities studied became substantially more precise in their gaze following as they got older. A model that assumed cross-cultural variation in average performance and developmental trajectories performed better than simpler models. Nevertheless, individuals did not cluster by community, which was shown by largely overlapping distributions. Individual differences were found in all age groups and communities.

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Second, we found that the gaze model proposed in Study II was applicable to every studied community. Matching the model prediction, children across all communities were more precise in locating the attentional focus of the agent when they gazed centrally compared to sideways. A model comparison with the center bias and random guessing models revealed overwhelming support for the gaze model.

Third, absolute differences in gaze-following precision could be partially explained by the data collection method. Children with no access to touchscreens were found to be less precise in the TANGO. Yet individual differences were still present in communities where 100% of children had access to touchscreens. Similar to Study I, we predicted that children with relatively more opportunities for social interaction within one community would show higher levels of gaze-following precision. However, we did not find any evidence for a relationship between gaze following and the collected demographic variables (e.g., size of household, number of children).

Overall, the findings of Study III suggested that children from diverse communities were remarkably consistent in the way they processed gaze, while individual differences were found everywhere.

#### **3.1.4 Results of Study IV**

As Study III relied on participants from diverse communities, the continuous version of the TANGO was further developed into the TANGO-CC by exchanging the animal stimuli for human stimuli and including 13 new instruction languages. Study IV described the design process of the TANGO-CC and examined the psychometric grounds for its use in cross-cultural data collection. For this purpose, we re-used the data set of Study III.

First, we provided a roadmap to our pragmatic approach to task development: Thoroughly assessing psychometrics of the basic TANGO version in a German setting (see Study I), while already working on the cross-cultural stimulus development and selection. The importance and added value of collaborating with local researchers and assistants was especially emphasized for creating the new stimulus set. The TANGO-CC's web app implementation proved highly useful in adapting the stimuli and enabling a swift data collection. Children from all over the world felt comfortable participating in the tablet study, regardless of whether they had previous touchscreen experience, and the extensive data set of Study III proved the viability of the TANGO-CC for cross-cultural data collection.

Second, the manuscript visualized the customizable components of the TANGO-CC. We featured a tutorial for how other researchers interested in using the TANGO-CC can adjust the task to their needs.

Third, and most prominently, we established the TANGO-CC's psychometrics across communities. Children from all communities performed better in training trials compared to test trials. Variation within communities (i.e., individual differences) greatly outweighed variation between communities. Split-half reliability estimates were calculated following three different approaches ((1) simple odd-even split, (2) a stratification by target centrality, and (3) a model-based age correction in addition to the stratification). All three approaches yielded similar results and speak for a high internal consistency across different communities.

Altogether, these findings underline the TANGO-CC's suitability to study gaze following across individuals and communities.

## 3.2 Research Contributions

The projects included in this dissertation contribute to a better understanding of child development from two different perspectives: (1) by extending our knowledge about meaningful variation in a core social-cognitive ability and (2) by providing modern, valid, reliable, and generalizable open-access tasks to other researchers. I will begin by first considering the theoretical aspects before moving on to the methodological contributions.

### 3.2.1 Theoretical Contributions

Our newly developed gaze-following task, the TANGO(-CC), has enabled us to study variation in one of the most fundamental social-cognitive abilities. We have focused on (1) the lifelong development of gaze following, (2) a mechanistic explanation of the cognitive processes behind it, (3) the relationship with other (social-) cognitive abilities (vector following, ToM, language), and (4) the universality of gaze following.

A large body of research has investigated the emergence of gaze following in infancy (for review, see Del Bianco et al. (2019)). Yet little was known about the further development once certain qualitative milestones are reached, for example, following gaze behind barriers or to locations behind

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themselves (Butterworth & Jarrett, 1991; Corkum & Moore, 1995; Deák et al., 2000; Moll & Tomasello, 2004). We could show that the precision in locating another's attentional focus does indeed increase until adolescence. By conducting Study II across the lifespan, we could identify the shape of change in gaze following: A rapid improvement in early childhood with a followed sequence of stability in adulthood (with a slight decline toward old age). This underlines that gaze following – like probably many other (social-) cognitive abilities (e.g., Raviv & Arnon, 2018) – continues to develop after it has reached its first qualitative milestones in infancy. This fits the fact that younger adults outperform older ones in their ToM abilities and the developmental trajectory follows a U shape (Henry et al., 2013; Rakoczy, 2022). Interesting and consistent research comes from Doherty and colleagues (Doherty et al., 2009, 2015). In nine different tasks (or task versions), Doherty et al. (2009) examined children's ability to explicitly judge what an agent is gazing at. They found that two-year-olds had difficulties passing these explicit gaze judgment tasks (verbally or by pointing), while children aged three and older showed increasing performance levels across tasks. Higher angular differences ( $15^\circ$  vs.  $10^\circ$ ) and a congruent head turn positively influenced children's gaze judgments, while the visual framing (i.e., distance between child and objects) did not affect their ability. The proportion of children's correct first looks and correct responses were highly correlated. The authors conclude that infants and preschoolers qualitatively differ in how they understand gaze: First, children can coarsely judge eye direction in a broader visual area, and only later children develop to perform finer gaze discriminations (Doherty et al., 2009). While the earliest instance of a social-cognitive ability might be informative for the prerequisites for this ability, studying its further development helps to illuminate where and why individuals differ from each other. At some point, most children will pass a dichotomous pass-or-fail test of gaze following. And yet these children differ in their social cognition and interaction competencies. Studying the refinement of social-cognitive abilities will help us to find out the underlying causes of diverse real-life outcomes.

We have proposed a tool for interpreting individual differences in gaze following, specifically in the form of a computational cognitive model. While existing theories have visualized gaze following as tracing a line of sight (Anstis et al., 1969; Symons et al., 2004; Todorović, 2006; Yaniv & Shatz, 1990), we have formulated this idea as a testable, well-defined mathematical model with explicit assumptions. Most importantly, we have included a conceptualization of individual differences. Our model assumes that individuals differ in their uncertainty around estimated pupil angles. This formulation also helps us to conceive development, namely as a reduction in the uncertainty around the pupil angles. The gaze model makes interesting group-level predictions. We could confirm that the distance

between the agent and their focus of attention (or, in other words, the centrality) influences people's precision in gaze following. This is consistent with results showing that 4.5-year-old children (Butterworth & Itakura, 2000) and 6-, 8-, 10-, 14-year-olds and adults (Vida & Maurer, 2012) were more accurate in identifying central compared to peripheral targets. A carefully designed, matched, non-social vector-following task correlated with gaze following, which highlights the importance of vector estimation in gaze following. This finding fits well with other research that underlines the spatial mechanisms in joint attention (Butterworth & Jarrett, 1991) and pointing (O'Madagain et al., 2019), highlighting the relevance of vector estimation in other areas of social cognition.

Developmental theories often highlight the importance of social interactions in children's social-cognitive development (e.g., Vygotsky, 1962, 1978, 1987). The hypothesis is that opportunities to observe, play, fight, and communicate with others highlight their unique mental states, which, in turn, facilitates the development of ToM and social cognition (Perner et al., 1994; Peterson, 2000; Zhang et al., 2021). Study I and Study II contribute to this body of research. In a German sample, weak positive relationships between gaze following and demographic predictors such as age of childcare entry pointed in the same direction.

Related to this is the question of how gaze following and perspective-taking are connected (Astor & Gredebäck, 2022). We could show that children's visual perspective-taking abilities predicted their imprecision levels in gaze following. Other ToM tasks did not relate to gaze following. We proposed that the cognitive processes underlying gaze following and perspective-taking might overlap as both abilities require considering another person's point of view. While other ToM tasks often rely on this component as well, they might entail more complex meta-representational aspects. For example, this could be an understanding that mental states can be false or aspectual in nature (Rakoczy, 2022) – concepts that are neither required for gaze following nor visual perspective-taking. Interestingly, Doherty et al. (2009) have proposed that children's emerging representational understanding of attention (as part of a ToM) could underline the importance of eye gaze in inferring the contents of another mind, which, in turn, could trigger the improvement in eye gaze discrimination in the preschool years: "Fine gaze discrimination develops slowly because it is not easy and, until the development of theory of mind, it is not necessary" (Doherty et al., 2009, p. 311).

A wide-spread notion is that gaze following supports language acquisition: Children are assumed to follow gaze to identify the referent of a new word (Bohn et al., 2022; Del Bianco et al., 2019; Tomasello, 2003). For example, Brooks & Meltzoff (2005) found that infants' gaze-following abilities

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predicted their language comprehension half a year later. Nevertheless, Astor & Gredebäck (2022) have argued that the relationship between language and gaze following remains inconclusive: A substantial amount of studies reported mixed evidence, lack statistical power, or combined gaze and point following into composite measures (see Figure 3 in Astor & Gredebäck (2022)). We addressed these issues by specifically focusing on isolated gaze following and leveraging a large data set to increase statistical power. Indeed, imprecision in preschool children's gaze following proved to be a substantial predictor for their receptive vocabulary six months later. This result helps to conclusively settle the research question on the relationship between gaze following and language development.

The proposed cognitive gaze model has demonstrated its relevance in cross-cultural research. We found substantial differences across communities in the absolute precision of children's gaze following. Had we simply compared those absolute values, we might have interpreted the findings in a way that eye gaze is processed differently across communities. Already Innis & Staddon (1989) have pointed out that "different performance patterns cannot be taken as evidence for different underlying mechanisms. And, symmetrically, similar performance cannot be taken as evidence for similar mechanisms" (p. 155). Consequently, they have argued for defining the formal mechanisms that regulate and describe behavior. By applying the gaze model and checking for its predicted signature patterns in the data, we could move away from the surface-level comparison and found evidence that children worldwide process gaze in similar ways – even though they differed in their certainty around the true pupil angles. Indeed, the gaze model might provide an exemplary framework for understanding how social cognition might be universal and yet vary (Kline et al., 2018) – a leading example to explain how "All people everywhere are different, *and* all people everywhere are the same" (Wellman, 2013, p. 69). These results are in line with Astor et al. (2022) and points to both universal and context-dependent aspects of gaze following in diverse communities.

Taken together, the included studies underline the added value of assessing variation in social cognition and show exemplary ways in which research questions benefit from an individual differences measure adapted for cross-cultural research. For practitioners in clinical or education settings, measuring an individual's social-cognitive ability might be even more relevant as this will help to monitor and support a child's unique development.

### 3.2.2 Methodological Contributions

After having considered how the presented studies have deepened our theoretical knowledge of variation in social cognition, or, more specifically, gaze following, I will now turn to the methodological contributions of this work.

Beaudoin et al. (2020) have argued that finding appropriate social-cognitive tasks for children remains difficult: Few tasks measure the ability in question in a continuous way and/or report empirically validated psychometric information. To solve the first issue, the TANGO exists in a categorical and continuous version which increases the flexibility for other interested researchers. Importantly, continuous here means that the experimental manipulation and the outcome measure are designed in a continuous format. To tackle the second challenge, we have provided a detailed psychometric analysis of the TANGO by assessing its validity, internal consistency, and retest reliability. Importantly, the TANGO-CC addressed the often-declared need for new tasks to assess social cognition across diverse communities. Satisfactory internal consistency estimates across 17 communities proved that the TANGO-CC is a reliable cross-cultural gaze following measure. In comparison to traditional gaze-following tasks (e.g., Astor et al., 2020; Byers-Heinlein et al., 2021; Gredebäck et al., 2010; Ishikawa et al., 2022), the TANGO(-CC) isolates eye movement alone and removes potential confounds with simultaneous head movements.

We have openly shared the stimulus pool and the source code of the TANGO(-CC). First, we hope this inspires other researchers to re-use the materials in their own projects. Especially the collection of cartoon-like human faces might prove helpful in designing new social cognition tasks that can be adapted for cross-cultural data collection. An exploratory analysis (see Supplements Study II) indicated that superficial stimulus modifications, such as using animal faces versus cartoon human faces, did not affect children's task performance. Second, we count on other researchers to follow this example and share their own materials according to Open Science principles. Providing psychometric information on a newly designed task and making it openly accessible will hopefully help to circumvent the "toothbrush problem" (Elson et al., 2023) – namely that researchers are reluctant to re-use tasks of other scientists.

The TANGO's code base could be recycled by other researchers to adapt the testing infrastructure for future tasks. It proved to be a very useful tool for collecting data at scale. The COVID-19 pandemic underlined the importance of flexible data collection strategies. The finding that in-person and

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remote data collection with the TANGO yielded similar results (see Study I) justifies the advance of new online methods and adds to the growing body of literature in this domain (Bohn, Le, et al., 2021; Bohn, Tessler, et al., 2021; Frank et al., 2016).

Two additional tasks that emerged as side projects in the context of this dissertation (see Appendix B) were designed under the same development principles and operated on very similar data collection platforms: the oREV and the Parent Report of Expressive Vocabulary in Children (PREVIC). The oREV is a child-directed measure. The task presents participants with four pictures, that is, one target and three distractors (phonological, semantic, and unrelated). A verbal prompt then asks participants to select the target. The initially larger item pool of the oREV included all 30 items of the Cross-linguistic Lexical Task (CLT) (Haman et al., 2015) and added 20 additional items to increase the task's difficulty and avoid ceiling effects for older children. By using IRT-modeling based on item difficulty and discrimination, the final item pool of the oREV could be decreased to 22 items. With regard to reliability, stability, convergent, and discriminant validity, the final task exhibits exceptional psychometric qualities in a German sample. To complement the picture of children's language development, the PREVIC serves as a parent-directed measure. Inspired by the MacArthur-Bates Communicative Development Inventories (CDI) for infants (Fenson et al., 2007; Fenson et al., 2012; Marchman & Dale, 2023), the PREVIC presents caregivers with a list of words and asks them which of these words their child has already spoken. Like the oREV, the PREVIC initially consisted of a larger item pool of 379 words and was specifically developed for (pre)school children. By leveraging the advantages of IRT, we created two task versions: a standardized version with a fixed number of 89 words, and an adaptive version that reduces the number of words based on the caregiver input while maintaining measurement accuracy. The PREVIC shows highly reliable results and convergent validity in a German sample. Up to this day, both tasks, the oREV and the PREVIC, are available only in German. However, the construction and implementation of the testing infrastructure will ease further adaptations to different languages. Furthermore, the web app platform greatly simplified collected large data sets (oREV:  $N = 581$ , PREVIC:  $N = 1190$ ) which is essential for an IRT-based task construction. These two tasks show the benefit of re-using the TANGO(-CC)'s testing infrastructure.

The web app implementation might tackle another challenge of child research: Developmental studies often report high drop-out rates, for example, because of children's fuzziness, fatigue, or lack of motivation (Slaughter & Suddendorf, 2007). Administering the TANGO has proven very helpful in this regard: Across communities, children tended to complete the task with ease and joy, and

often even asked for a repetition. Not only did this allow for many trials per child, but it also meant that drop-out rates could be greatly reduced. Allen et al. (2024) have recently promoted games as intuitive, rewarding, engineered research environments. The authors have argued that online games enable studying various domains of cognition with the potential of higher ecological validity, increased participant diversity, cross-cultural suitability and adaptability, and large-scale data sets. Our self-made, game-like design of the TANGO(-CC) leverages these advantages while retaining maximum experimental control.

The TANGO(-CC)'s task design enabled a large-scale cross-cultural data collection. Adopting study designs for cross-cultural research is often time-consuming and, therefore, done for each community separately (e.g., Mehta et al., 2011). The modular structure of the TANGO-CC and the usage of SVGs ease this process by providing customizable building blocks. Task instructions are embedded as pre-recorded audio files. This way, the training of the experimenters can be streamlined, and there is little room for experimenter errors or biases. Without these features, we could not have collected data from more than a thousand children across five different continents within a time frame of 22 months.

Finally, we want to highlight the diversity of the TANGO-CC data set from Study III. Participants lived in various kinds of social, cultural, political, and ecological systems, using different languages and subsistence styles. Previous cross-cultural research has often focused on comparing communities from the urban Global North to communities from the rural Global South (Barrett, 2020b). We overcame this common pitfall of a dichotomous comparison by providing a more complete, more inclusive picture of the different environments in which children grow up.

### 3.3 Limitations

While the studies included in this dissertation have shown their strengths and unique research contributions, they must be considered against some limitations.

First of all, I want to draw attention to the modification in terminology. While Study I has stated that the TANGO measures *gaze understanding*, we have switched to the term *gaze following* in Study II, Study III, and Study IV. We have defined gaze understanding as “the ability to locate and use the attentional focus of an agent” (Prein, Kalinke, et al., 2024, p. 2471) and gaze following as “turning one's eyes in the same direction as the gaze of another agent” (Prein, Kalinke, et al., 2024, p. 2471)

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or as “the ability to identify the attentional focus of another agent” (Prein, Bednarski, et al., 2024, p. 9). In Study I, we have argued that the TANGO’s pre-requisite is gaze following and that it not only includes this component but also an action toward the gazed-at location (i.e., clicking at the target location), which would resemble real-life situations in which we apply social information to advise our own behavior. However, a reviewer of Study II questioned whether the term “gaze understanding” appropriately captures the construct that the TANGO measures. They argued that the TANGO mainly involves estimating gaze directions, and the cognitive and perceptual underpinnings remain unclear. The phrase “understanding” might overestimate children’s ability and might imply a more representational processing than is actually needed for, or measured by, the task itself. Consequently, we have adopted the term gaze following, which is more consistent with the existing literature and does not suggest any representational processing or conceptual understanding.

Regarding the task design, it might be questioned whether the TANGO(-CC) is “social enough.” As Study II showed, participants’ performance in the task related to a moderate degree to their ability to estimate (non-social) vectors in space. Some scholars might question whether a task can still be considered to measure an aspect of social cognition if it relies on physical cognition abilities. The answer to this critique might depend on our definition of social cognition. If we base our definition of social cognition on its function or area of application, the TANGO(-CC) can clearly be considered a social-cognitive task: The task requires participants to estimate another person’s visual attentional focus, which is a social cue. Alternatively, we could base our definition of social cognition on the context in which the ability is or was acquired. Was a certain ability honed and shaped by experiences within the social domain or was it developed through more general experiences in other domains (e.g., spatial contexts)? While we cannot empirically answer this question, I believe it is likely that children learn to estimate (gaze) vectors through more and more experience in social perspective-taking. Given the sheer amount of social interactions children engage in and its mostly rewarding nature, it is likely that they hone the ability to follow (gaze) vectors through social experiences. Estimating (gaze) vectors could emerge so that children can successfully interact with others, while the ability to estimate vectors in space could still be generalized to serve other functions in different domains as well. Lastly, we could base our definition of social cognition on its underlying cognitive processes or mechanisms. As we have seen, the task requires participants to estimate vectors in space. As such, the TANGO(-CC) taps into an ability that is not specific to social interactions. I would argue that most (if not all) social-cognitive abilities comprise skills from other domains. For example, consider the classical FB Sally-Anne change-of-location task (Baron-Cohen

et al., 1985; Wimmer & Perner, 1983). Here, participants need a certain level of object permanence (i.e., understanding that the ball continues to exist in the box even when it cannot be seen) and causality understanding (i.e., moving a ball has consequences for where it is located) to pass the task. Social cognition might, in general, rely on some physical-cognitive abilities – as Butterworth & Jarrett (1991) said: “What minds have in common is space” (p. 55).

Stimuli of the TANGO(-CC) are presented on a screen, and participants do not actively engage in a participatory social interaction. Researchers have pointed out that we may process social information differently when we interact directly with others than when we simply observe them (Risko et al., 2012; Schilbach et al., 2013). Slaughter & Repacholi (2003) have argued for differentiating between competence (i.e., how an individual responds to social-cognitive tasks in a laboratory setting) and performance (i.e., how an individual applies social-cognitive abilities to contexts in their day-to-day life). We cannot be certain that the TANGO(-CC) qualifies to measure children’s daily performance in gaze following. Yet first evidence points in the direction that the TANGO taps into real-life social cognition. Children’s perspective-taking abilities were related to imprecision in the TANGO but less so to a matched, non-social vector following task (in Leipzig, Germany). Additionally, the relationship to family-level demographics (e.g., age of childcare entry) suggests that the TANGO captures a social aspect of children’s development.

The proposed cognitive model of gaze following estimates an inference parameter that describes participants’ uncertainty around the true pupil angles. While the model gained substantial evidence, the risk of oversimplification exists: Potentially, we have missed other parameters that comprise gaze following or explain the performance in the TANGO. For example, a motor noise parameter could be helpful to model how accurately participants click on the location that they wanted to click. In addition, the conducted model comparisons (against a center bias and random guessing model) might profit from more complex alternative models. We have suggested a line-of-sight approach with and without motor noise in the Supplementary materials of Study II. While these can explain how participants solve the TANGO, they do not model individual differences in participants’ inferential abilities and do not recover the U-shaped pattern as predicted by the gaze model and as found in the data. Competitive, realistic alternative models to our gaze model remain to be established. Finally, the proposed gaze model cannot explain whether the development of increasingly precise gaze following (i.e., the decrease in imprecision in the task performance, and the decrease in uncertainty around the pupil angles in the model) appears due to physical, cognitive, or emotional changes. Physical changes might include a maturation in visual acuity (though unlikely for pre-

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school children), cognitive changes might include a greater sensitivity to social information or an increased comprehension that eye gaze can be used as a cue, and emotional changes might include a higher motivation to focus on other agents as children get older. These and many other factors could drive the refinement of gaze-following precision, are mutually compatible with the proposed gaze model, and need further examination.

The TANGO allowed us to employ the same study design from early childhood into late adulthood, which eases a direct quantitative data comparison. Yet applying the same study design does not necessarily entail capturing the same underlying constructs in all age groups. Longitudinal or developmental measurement invariance means that a task validly measures the target phenomenon at different ages to be both valid at each age and comparable across ages (Skinner et al., 2019). Factors like familiarity with the data collection method or stimuli might influence participants' performance in a task (see effect of touchscreen experience in Study III). While the developmental trajectory found in Study II suggests that participants with older age had no issues completing the TANGO, future studies should further investigate its longitudinal/developmental measure invariance (Petersen, 2023).

Children with no prior touchscreen access showed slightly larger imprecision levels in the TANGO-CC. These technology effects remain important consider when applying the TANGO-CC and interpreting the results across communities. Noticeably, communities in which all children had access to touchscreens still showed individual differences. This underlines that not all variation can be attributed to different levels of technology exposure. Additional variables that could predict children's performance in the TANGO-CC need to be examined.

Regarding the cross-cultural gaze-following study (see Study III and Study IV), several limitations come to mind. First, the sample selection might be questioned. Selection of the included communities in Study III relied on convenience sampling and was not driven by theoretically relevant dimensions or selecting maximally different populations (Boehnke et al., 2011; Nielsen et al., 2017). At worst, this could have left us missing a crucial component or axis of variation in the cognitive component that we studied (Apicella et al., 2020). Furthermore, it should be noted that the samples included urban and rural communities in the Global South, while participants from the Global North all lived in urban environments. As Broesch et al. (2023) highlighted, "Cross-cultural variability also exists 'at home', including in communities with different migration histories, or across regions" (p. 603) – and therefore, including diverse communities within the Global North could have

strengthened the study's findings. Relatedly, we only measured very rough proxies of environmentally and culturally relevant factors (e.g., household size). Interpreting our findings would have benefited from a deeper understanding of each community's contextual factors (Broesch et al., 2023). Another point of critique concerns the methodological approach of the TANGO-CC. While the task was designed with constant input from local collaborators, the original brainstorming, organization, and implementation process was mainly based in Leipzig, Germany. Cross-cultural research would benefit from more community-based, participatory, decolonized methods development throughout all stages of the research process (Bermúdez et al., 2016; Grant et al., 2022; Stanton, 2014). Finally, the choice of cross-cultural stimuli and the presentation mode can be criticized. While participants of the included communities in Study III seemed to behaviorally respond to and interpret the stimuli similarly, we could have put more effort into choosing a locally relevant target object (see Broesch et al., 2023; Kline et al., 2018). A balloon might simply not be equally frequent or relevant in all studied communities.

Analogously, presenting the TANGO-CC on a computer screen might complicate the interpretation of findings across communities, as children were differentially exposed and familiar with the presentation device (Broesch et al., 2023; Hruschka, 2020). The effect of touchscreen exposure on children's imprecision in the task highlights this point. The study might have benefited from adjusting the task format and/or relying on multiple methods to measure children's gaze-following abilities (Broesch et al., 2023).

## 3.4 Outlook

There remain many interesting research avenues that would benefit from an individual differences perspective on social cognition. I will first focus on those that could be studied by modifying the current version of the TANGO(-CC), and then move on to broader, more theoretical research questions.

### 3.4.1 Possible Spin-offs of the TANGO

The modular structure of the TANGO(-CC) enables swift modifications of the stimuli and experimental design. Here, I provide first ideas on how to apply, modify, and extend the task to answer new research questions around gaze following or other related constructs.

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Initially, we developed two task versions of the TANGO, with one discrete and one continuous outcome measure (see Study I). The studies that followed (see Study II, Study III, and Study IV) all relied on the continuous task version. While the continuous version of the task shows slightly better psychometric properties (especially regarding the internal consistency, see Study I), the discrete version of the TANGO might be more helpful for other research questions. First, it is noteworthy that the task difficulty can be easily adjusted by varying the number of boxes between two and eight. With some additional programming efforts, the box version could be turned into an adaptive testing setup: Participants could start with a small number of boxes, and once they succeed in a given trial, the difficulty is adjusted and more boxes are shown. This might help implement a training intervention or study children's learning curves in gaze following. Second, the boxes in the discrete version could be modified into different colors or forefronts. The appearance of the boxes could be matched to some features of the agent: For example, a monkey and a box with a banana sticker in the front, or a girl wearing blue shorts and a t-shirt with a blue box. Phenomena such as group identity, prior knowledge, or diverse desires could be studied in this way. Another example could be action prediction, that is, the question of whether children could anticipate to which box an agent would gaze toward depending on some characteristical feature of the agent.

The youngest participants in Study II (especially the three-year-olds) showed high levels of imprecision in the TANGO. This might be due to the subtle gaze cues. Existing studies found that already three- to four-month-olds can follow gaze (e.g., D'Entremont et al., 1997). However, "It is worth noting that the accuracy of infants' gaze localization abilities is not known. The measure used in gaze-following experiments is often no more precise than whether infants look to the correct side" (Doherty et al., 2009, p. 309). The TANGO(-CC) could be adapted to include a head movement of the agent. Comparing the task with and without head movement would allow us to disentangle the importance/saliency of both components (i.e., eyes and head) for children's precision in locating an attentional focus.

Alternatively, younger children might have been less precise (see Study II) because they were less intrinsically motivated than older participants or did not understand that precision is the task's goal. The TANGO(-CC) could be modified to include rewards depending on a child's precision level. For example, a rewarding tune or video clip could be played. The presentation of the tune/video could become longer the more precise a child located the target. This design might (1) increase children's motivation to be precise, (2) help to keep children engaged in the task, and (3) provide a measure of children's potential learning curve in gaze following (comparing earlier with later trials). The

task instructions could, furthermore, highlight that participants can take their time until they are confident in their choice. This could reduce a potential confound between faster response times and higher imprecision levels (known as speed-accuracy trade-off (Zaal & Thelen, 2005)). However, please note that in an exploratory analysis, no relationship between response time and imprecision in the TANGO was found.

In the limitations section, I have discussed whether the TANGO(-CC) is “social enough.” One idea to increase the social context of the task is to create a prior social interaction between the participant and the agent on screen. In a spin-off attempt (<https://github.com/ccp-eva/gafo-cc/tree/playground>), I have created a task version in which the participant can guide where the agent looks: The participant can click on any location on the screen, and the agent then gazes at exactly this location. While this certainly remains an interaction on screen, it does enhance the second-person perspective and may underline the shared intentionality between the agent and the participant.

Another idea to increase the social aspects of the task would be to design a joint attention version. Here, the agent could alternate their gaze between the balloon and the participant. This might underline the intention of the agent to guide the participant to the balloon location and potentially increase the participants’ motivation to follow the agent’s gaze. It might be worthwhile to first investigate how participants behave when the agent only shows saccade eye movement to the target location. Having the agent’s gaze only shortly available to the target location might increase the TANGO(-CC)’s difficulty.

The cognitive model of gaze following (see Study II) assumes that participants integrate information of the agent’s left and right eye to estimate their attentional focus. Potentially, integrating the information is especially important for the more challenging target locations to the sides. The TANGO(-CC) could easily be adapted to test this claim. For example, the agent could be modified into a playful, alien-like appearance which would make it possible to vary the number of eyes (e.g., one vs. three eyes). This setup could help to disentangle which pupils the participants rely on to estimate the focus of attention.

Another assumption of the gaze model is that participants are biased towards the screen center. We could explore which components lead to this center bias by creating new starting scenes in the TANGO(-CC): The position of the agent and the starting point of the balloon could be varied. For example, the agent could be positioned on the very left- or right-hand side of the scene. Furthermore, we could modify the direction of the balloon’s trajectory. So far, the balloon’s final position varies

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on the horizontal plane. We could estimate whether difficulties vary when the balloon varies on the vertical plane – which has been shown to develop later in gaze following (Silverstein et al., 2021).

Most importantly, the current version of the TANGO(-CC) results in different distances for different target positions: The very far left and right target positions yield the longest balloon trajectories. Together with the characteristics of distributions in the gaze model, this results in the prediction that participants show greater imprecision in trials where the balloon lands sideways. An alternative setup could employ a circle-based design (G. Gredebäck, personal communication, July 14, 2022). Imagine a clock. The agent and balloon starting position would be in its center. This time, however, the balloon would fly in all possible directions like watch hands pointing at the 12 different hours. Importantly, the movement radius of the balloon would stay the same so that it always covers the same distance. This alternative design could circumvent the potential diffusion between participant precision and balloon distance, allowing us to refine the cognitive gaze model.

Lastly, a touchscreen familiarization could be completed before participants start the TANGO(-CC). This might be especially helpful for participants with no or little technology exposure (see Study III). One idea would be implementing a bubble-wrap game where participants can crush little air pockets (or even balloons) by quickly clicking on them. This design could accustom participants to be precise, determined, motivated, and quick in their touchscreen responses. Of course, touchscreen trainings like this would benefit from the existing testing infrastructure of the TANGO(-CC).

#### **3.4.2 Open Research Questions**

While we have successfully studied gaze following from early childhood into old age, we have relied on a cross-sectional study design. Future research could employ the TANGO(-CC) in a longitudinal study to investigate how children develop and refine their gaze-following abilities throughout their childhood. Combining such efforts with collecting demographic variables and other (social-) cognitive abilities would result in a more fine-grained understanding of helping and hindering factors in this development.

So far, the TANGO(-CC) has been presented as an active behavioral task. Future research could apply eye tracking with the TANGO(-CC). This would have several advantages. First, by moving away from an active behavioral choice, younger infants could be included. This would complete the lifespan perspective from Study II and enable testing the cognitive gaze model for this age

group. Other research has suggested an alternative mechanism for gaze processing based on luminance (Ando, 2002; Doherty et al., 2009, 2015), where the darker side of the eye (iris and pupil) compared to the bright sclera marks the perceived gaze direction. This process might be less accurate but computationally lighter, potentially explaining how infants process gaze (Doherty et al., 2009, 2015). Disentangling the processing mechanisms of infants' gaze following and comparing alternative computational models remains an interesting open research area. Second, with the help of an eye-tracking study, we could compare touch and gaze behavior (see Doherty et al., 2009). This might be especially interesting for children who are imprecise in their touch behavior. Do these children look exactly where the agent is gazing and are just imprecise in their touch behavior? Or do they rather already look imprecisely and touch exactly where they themselves have followed the agent's gaze? The interplay or match between looking and touching behavior might prove helpful in identifying the sources of errors, which, in turn, would be very informative for computational modeling work (Hoffman & Walters, 2022).

Our proposed gaze model established a process-level theory of how people estimate another agent's point of attention. What it does not include is a theory on the emergence of gaze following in the first place. It remains unclear which mechanisms drive children to start following eye gaze (Astor & Gredebäck, 2022). Existing theories place different emphasis on children's innate abilities (Baron-Cohen, 1995; Batki et al., 2000), their social awareness, and motivation (Astor et al., 2020; Friesen & Rao, 2011; Ishikawa et al., 2020; Meltzoff, 2007; Tomasello, 1999), or their propensity for reinforced learning (Corkum & Moore, 1998; Silverstein et al., 2021; Triesch et al., 2006). Testing these theories against each other and disentangling potential driving forces in the development of gaze following remains an interesting open research avenue.

The TANGO(-CC) focuses on detecting gaze direction, and as such, more on the participant's passive role as a gaze observer and the information-acquiring and processing perspective. However, eye gaze has been said to fulfill many different functions in social interactions: Eye gaze might signal a warning, a communicative intention, or an emotional state (e.g., Argyle et al., 1973). Recent research by Gerlofs et al. (2022) has started to investigate the communicative component of gaze by studying adults' looking behavior during a hide-and-seek game. Future research could investigate the developmental origins of the different gaze functions and how children decide how to direct their own gaze.

We have seen that developmental theories often assume that social interactions shape social-

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cognitive abilities. For example, infants are particularly responsive to contingencies experienced during daily interactions with their caregivers (Akhtar & Gernsbacher, 2008; Bigelow, 1998; Bigelow & Birch, 1999; Bigelow & Rochat, 2006). In Study I, we found suggestive evidence that social interaction opportunities correspond to higher precision levels in gaze following. However, this claim needs further empirical justification. Most importantly, we need good measures on both ends: for the social-cognitive abilities in question but also for children's daily social interactions. The parental questionnaire applied in Study I could only serve as a rough proxy for children's daily interactions. What is needed are more fine-grained tools to capture children's lived experiences. Modern machine learning and computer vision advancements seem to be a promising avenue in this regard (Bergelson et al., 2023; Donnelly & Kidd, 2021; Duan et al., 2017; Isaev et al., 2024; Long et al., 2023; Malmir et al., 2013; McMahon & Isik, 2023). Furthermore, we could not replicate the relationship between gaze following and the number of siblings in the cross-cultural sample (see Study III). Cross-culturally assessing these family-level variables in more detail could help to illuminate which interactions affect children's social cognition.

The relationships between gaze-following precision and language abilities, non-social vector following, and perspective taking were only assessed in a sample from the Global North (Leipzig, Germany). Future research could investigate said relationships in more diverse communities to test whether they are generalizable.

The studies included in this dissertation focus on gaze following as an important cornerstone for a child's social-cognitive development. While face-to-face interactions and eye contact are highlighted in Western culture, other communities might focus more on other social and communicative cues (Kline et al., 2018). Akhtar & Gernsbacher (2008) have cautioned to exclusively rely on gaze following as a measure of social engagement and attention/intention understanding. Similarly, Doherty et al. (2009) have stated that "body direction and posture, and particularly head direction, are more useful cues to engagement than is eye direction" (p. 310). Future studies should examine how other senses, such as tactile and/or verbal modalities (e.g., touch, prosody, voice direction), are used across diverse communities to determine the attentional focus of another agent (Akhtar & Gernsbacher, 2008; Kline et al., 2018; Wefers et al., 2023). An example of such work comes from Bard et al. (2021), who have proposed a culturally inclusive concept of *joint engagement* which allows for these expressions in other modalities and with more diverse social partners and topics. Indeed, traditional visual joint attention episodes were more common in Western communities. At the same time, "triadic connectedness" was observed in infants coming from a community in the

U.K., from a Nso community in Cameroon, and an Aka community in the Central African Republic (Bard et al., 2021). While this study follows a commendable inclusive approach, it can nevertheless be questioned whether the study's conceptualization and operationalization of joint engagement are well-defined and clear-cut enough to allow for meaningful conclusions.

To come back to the introduction, the field of comparative studies on gaze following could be expanded to further assess the characteristics of social cognition that (arguably) make us uniquely human. Existing research has shown that great apes and other mammals can follow gaze (Kano & Call, 2014; Rosati & Hare, 2009; Tomasello et al., 1998; for review, see Itakura, 2004). For example, like one- to one-and-a-half-year-old human infants, chimpanzees can follow gaze to locations behind them (Povinelli & Eddy, 1997). However, conflicting findings exist on whether non-human great apes follow gaze mainly based on the eye direction alone or a combination of head and eye movement (e.g., Povinelli et al., 1997; Tomasello et al., 2007). In addition, Itakura (2004) concluded their review by arguing that it is unclear if and which non-human great apes understand the "seeing-knowing relationship" (p. 217): In other words, understanding the eyes as a source of knowledge, and consequently, gaze as affecting mental states. To further test the great apes' understanding of gaze, the TANGO(-CC) could be adjusted for comparative use: How would non-human great apes perform in this gaze-following task? Studies could either rely on tracking the eye gaze of the apes (e.g., Krupenye et al., 2016) or employ a touchscreen format. Many of the chimpanzees, gorillas and orang-utans at the Wolfgang Köhler Primate Research Center in Leipzig, Germany, have gained experience with participating in touchscreen studies (Allritz et al., 2021; Close & Call, 2015; Margotoudi et al., 2019; Munar et al., 2015), and the TANGO(-CC) might prove feasible for this testing setup.

While the studies included in this dissertation focus on social cognition and gaze following, we also invented a new continuous task of non-social vector following (see Study II). Having this task at hand, we could examine whether vector estimation is needed for other social-cognitive abilities. For example, predicting an action of another agent (e.g., pointing or reaching for a cup) might rely on estimating vectors in space (O'Madagain et al., 2019). Studying how social- and non-social cognitive abilities interact with each other will help us to disentangle the (inter) independence of our core cognitive processes.

Future studies could investigate individual differences in other, potentially more complex social-cognitive abilities. In the introduction, I have described a short expert survey on social cognition.

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Additionally to questions concerning the definition of social cognition, we compiled a list of 21 social-cognitive abilities. We asked experts to judge the likelihood of individual differences within these abilities; that is, how children of the same age would vary in performing these abilities. The experts assumed that children varied mostly in manipulating emotions, deceiving others, simulating others' reasoning processes, taking another's perspective, and understanding the subjectivity of knowledge states. Abilities that were assumed to vary the least between children of the same age were recognizing agents and following gaze. It appeared that experts assumed variation in many social-cognitive abilities and judged more room for individual differences the more complex a given social-cognitive ability. Interestingly, the studies included in this dissertation have shown that children do vary even in gaze following. However, the variation is clearly not about *whether* children follow gaze but *how precisely* they do so. It remains an interesting open research avenue to assess how children vary in more complex social-cognitive abilities.

One example of such an ability could be how children learn to distinguish different knowledge states. A classical test of understanding knowledge access comes from Wellman et al. (2001): Here, children see the content of a box and need to judge whether another ignorant agent knows what is inside this box. Like the Sally-Anne FB task, the outcome variable is dichotomous and does not leave much room for measuring children's increasingly fine-grained social cognition. In a preliminary pilot study, we have begun implementing a continuous outcome measure that captures children's sensitivity to gradual knowledge states (Differentiating Incomplete States of Knowledge-Open (DISKO); <https://github.com/ccp-eva/disko>). Children witness how an agent walks with her pet into a hut. They walk along one out of several paths that are built like a decision tree. Familiarization trials show children that the agent and the pet always want to reach the same hut. In the test trials, the agent witnesses differing amounts of the pathway that her pet is walking. For example, the agent sees her pet taking the very first turn to the left, but then a telephone rings, and the agent has to leave. The pet continues to walk the pathway into one of the huts. The agent returns and children are asked to predict to which hut the agent will go. They can distribute stickers across all options. For children that show knowledge-ignorance understanding, they should vary their sticker distribution so that it matches the epistemic state of the agent (i.e., placing no stickers on huts that the agent can exclude as the pet's location; and equally placing sticker on the huts where her pet could be). As such, the DISKO could measure children's action prediction in situations where the agent has gradually varying knowledge access.

Computational cognitive modeling might prove helpful in describing and predicting this social-

cognitive ability. A potential model could involve two model parameters:  $\beta_1$  and  $\beta_2$ . The parameter  $\beta_1$  would capture children's sensitivity to differences in knowledge states based on differential perceptual input, and the parameter  $\beta_2$  would capture how much children get biased or distorted by reality (i.e., action prediction based on the agent's belief or the world state as in the pet's actual location). The gaze model proposed in Study II could potentially serve as one of the components that make up  $\beta_1$ . The parameter  $\beta_2$  could potentially be useful for modeling FB understanding. This proposed study idea highlights (at least) two new research aims. First, it highlights how new study designs could measure social cognition in a more continuous, fine-grained manner so that individual differences can be captured – eventually building up a new social cognition task battery. Second, it underlines the appeal of modeling social cognition. Cognitive models could build up on each other and break down the components needed to master a certain ability (Baker et al., 2017). Potentially, we could assess whether gaze following is, indeed, a fundamental part of other social-cognitive abilities.



## 4 Conclusion

In this dissertation, I have questioned the widespread practice of overlooking individual differences or regarding them as measurement error or noise, and have shed new light on existing variation in social cognition. I have shown the added value of this perspective on the concrete example of gaze following across individuals, ages, and communities. The studies included in this dissertation have reported the development, psychometric assessment, and application of a new task to measure individual differences in gaze following. The extensive evaluation of the TANGO and the TANGO-CC, respectively, constitutes an exception in the field of social-cognitive studies. Administering the TANGO(-CC) has enabled us to gain a comprehensive, multi-perspective view on gaze following and decipher the universal cognitive processes behind it. A computational cognitive model showed that children and adults follow gaze by estimating pupil angles and, consequently, gaze vectors that run from the center of the eye through the pupil. The development of gaze following and individual behavioral differences can be explained by varying amounts of uncertainty in this noisy inference process. The proposed gaze model could describe children's gaze following in 17 diverse communities worldwide, which speaks for a universal cognitive process in estimating gaze directions. Furthermore, gaze following is related to children's receptive vocabulary, proxies of social interaction opportunities, non-social vector following and perspective-taking abilities (in a German child sample). In sum, this dissertation illustrates how combining reliable tasks, formal theoretical models, and cross-cultural research enables us to study the development and mechanisms of social cognition – precisely those abilities that make us arguably uniquely human.



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# Appendix A — Overview of Articles

## Included in the Dissertation

Article No.	Bibliography	Publication Status	Specific Contribution	Weighing Factor
1	Prein, J. C., Kalinke, S., Haun, D. B. M.*, & Bohn, M.* (2024). TANGO: A reliable, open-source, browser-based task to assess individual differences in gaze understanding in 3 to 5-year-old children and adults. <i>Behavior Research Methods</i> , 56(3), 2469–2485. <a href="https://doi.org/10.3758/s13428-023-02159-5">https://doi.org/10.3758/s13428-023-02159-5</a>	Published	Co-author with predominant contribution. J.C. Prein: Conceptualization, Software, Formal Analysis, Writing - Original Draft Preparation, Writing - Review & Editing.	1
2	Prein, J. C., Maurits, L., Werwach, A., Haun, D. B. M.* & Bohn, M.* (2024). Variation in gaze following across the life span: A process-level perspective. <i>Developmental Science</i> , 27(6), Article e13546. <a href="https://doi.org/10.1111/desc.13546">https://doi.org/10.1111/desc.13546</a>	Published	Co-author with predominant contribution. J.C. Prein: Conceptualization, Methodology, Software, Investigation, Formal Analysis, Writing - Original Draft Preparation, Writing - Review & Editing.	1
3	Bohn, M.*, Prein, J. C.*, Ayikoru, A., Bednarski, F. M., Dzabatou, A., Frank, M. C., Henderson, A. M. E., Isabella, J., Kalbitz, J., Kanngiesser, P., Keşsafoğlu, D., Koymen, B., Manrique-Hernandez, M., Magazi, S., Mújica-Manrique, L., Ohlendorf, J., Olaoba, D., Pieters, W., Pope-Caldwell, S., ... Haun, D. (2024). <i>A universal of human social cognition: Children from 17 communities process gaze in similar ways</i> . [Manuscript under review]. PsyArXiv. <a href="https://doi.org/10.31234/osf.io/z3ahv">https://doi.org/10.31234/osf.io/z3ahv</a>	Under Review	Co-author with equal contribution. J.C. Prein: Conceptualization, Methodology, Software, Investigation, Writing - Review & Editing	1
4	Prein, J. C., Bednarski, F. M., Dzabatou, A., Frank, M. C., Henderson, A. M. E., Kalbitz, J., Kanngiesser, P., Keşsafoğlu, D., Koymen, B., Manrique-Hernandez, M., Magazi, S., Mújica-Manrique, L., Ohlendorf, J., Olaoba, D., Pieters, W., Pope-Caldwell, S., Sen, U., Slocombe, K., Sparks, R. Z., ... Bohn, M. (in press). Measuring variation in gaze following across communities, ages, and individuals – a showcase of the TANGO-CC. <i>Advances in Methods and Practices in Psychological Science</i> . Link to preprint: <a href="https://doi.org/10.31234/osf.io/fcq2g">https://doi.org/10.31234/osf.io/fcq2g</a>	In press	Co-author with predominant contribution. J.C. Prein: Conceptualization, Formal Analysis, Methodology, Project administration, Resources, Software, Visualization, Writing - Original Draft Preparation, Writing - Review & Editing	1

\* denotes shared first or last authorship

## **Presentation of the Articles on Conferences**

**Article No 1:** Prein, J., Bohn, M., Haun, D. (2021). Social-cognitive development from an individual differences perspective. Virtual talk presented at the 28th Conference of the European Society for Philosophy and Psychology conference in Leipzig-Online. <https://philevents.org/event/show/91814>

**Article No 1:** Prein, J., Bohn, M., Haun, D. (2021). Social-cognitive development from an individual differences perspective. Talk presented at the 4th Konstanz summer school on internet-based data collection and analysis. <https://www.psychologie.uni-konstanz.de/en/4th-summer-school-on-internet-based-data-collection-and-analysis/>

**Article No 2:** Prein, J., Bohn, M., Haun, D. (2022). Modeling individual differences in children's understanding of gaze cues. Virtual talk presented at the Budapest CEU Conference on Cognitive Development. <https://cdc.ceu.edu/bcccd22>

**Article No 2:** Prein, J., Bohn, M., Maurits, L., Haun, D. (2022). Measuring and modeling individual differences in children's understanding of gaze cues. Poster presented at the 3rd Joint Meeting of the Society for Philosophy and Psychology & European Society for Philosophy and Psychology in Milan. <https://www.europeanspp.org/meetings.html>

**Article No 2:** Prein, J., Bohn, M., Maurits, L., Kalinke, S., Haun, D. (2022). Modeling individual differences in children's understanding of gaze cues. Poster presented at the Computational Summer school on Modeling Social and collective behavior in Konstanz. <https://www.exc.uni-konstanz.de/collective-behaviour/research/education/cosmos-computational-summer-school-on-modelling-social-and-collective-behaviour/>

**Article No 2:** Prein, J., Bohn, M., Haun, D. (2022). From gaze understanding to knowledge attribution: Designing tasks to measure individual differences in social cognition. Talk presented at the University of Göttingen. Personal invitation.

**Article No 3:** Prein, J., Olaoba, D., Stengelin, R., Bohn, M., Haun, D. (2023). The development of gaze understanding across (at least) 6 diverse societies. Talk presented at the Budapest CEU Conference on Cognitive Development. <https://cdc.ceu.edu/bcccd23>

**Article No 3:** Prein, J., Bohn, M., Maurits, L., Kalinke, S., Haun., D. (2023). Measuring individual differences in social-cognitive development. Poster presented at the 14th Dubrovnik Conference on Cognitive Science. <https://ducog.cecog.eu/past-conferences>

**Article No 4:** Prein, J., Stengelin, R., Haun, D., Bohn, M. (2024). TANGO-CC: A customizable open-source task to study gaze understanding across cultural settings. Lightning talk presented at the Culture Conference Zurich. <https://www.comparativelinguistics.uzh.ch/en/news/2024/2024-02-9-watson.html>

## **Declaration According to § 16 of the Guideline for Cumulative Dissertations**

I avouch that all information given in this appendix is true in each instance and overall.

Hamburg, [Date]

[Signature]

The full texts of the included manuscripts are provided below. For the accepted articles, the published versions are provided. For articles under review/currently in press, the submitted /accepted versions are provided which are published online as pre-prints.

# Study I

Behavior Research Methods (2024) 56:2469–2485  
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## TANGO: A reliable, open-source, browser-based task to assess individual differences in gaze understanding in 3 to 5-year-old children and adults

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### Abstract

Traditional measures of social cognition used in developmental research often lack satisfactory psychometric properties and are not designed to capture variation *between* individuals. Here, we present the TANGO (Task for Assessing Individual differences in Gaze understanding-Open); a brief (approx. 5–10min), reliable, open-source task to quantify individual differences in the understanding of gaze cues. Localizing the attentional focus of an agent is crucial in inferring their mental states, building common ground, and thus, supporting cooperation. Our interactive browser-based task works across devices and enables in-person and remote testing. The implemented spatial layout allows for discrete and continuous measures of participants' click imprecision and is easily adaptable to different study requirements. Our task measures inter-individual differences in a child ( $N = 387$ ) and an adult ( $N = 236$ ) sample. Our two study versions and data collection modes yield comparable results that show substantial developmental gains: the older children are, the more accurately they locate the target. High internal consistency and test-retest reliability estimates underline that the captured variation is systematic. Associations with social-environmental factors and language skills speak to the validity of the task. This work shows a promising way forward in studying individual differences in social cognition and will help us explore the structure and development of our core social-cognitive processes in greater detail.

**Keywords** Social cognition · Individual differences · Gaze cues · Cognitive development

### Introduction

Social cognition—representing and reasoning about an agent's perspectives, knowledge states, intentions, beliefs, and preferences to explain and predict their behavior—is among the most-studied phenomena in developmental research. In recent decades, much progress has been made in determining the average age at which a specific social-cognitive ability emerges in development (Gopnik & Slaughter, 1991; Peterson et al., 2012; Rakoczy, 2022; Wellman et al.,

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2001; Wellman & Liu, 2004). Yet, there are always individual differences. Identifying variability in social-cognitive abilities and factors influencing their development is vital in theory building (e.g., to test causal predictions) and designing interventions (Happé et al., 2017; Kidd et al., 2018; Lecce et al., 2014; Mundy et al., 2007; Underwood, 1975).

Numerous studies have already examined individual differences in social cognition (for an overview, see Hughes & Devine, 2015; Slaughter, 2015). The most common, recurring research questions are concerned with the developmental sequence of social-cognitive abilities (e.g., Wellman & Liu, 2004), and which factors drive the development of social cognition (Devine & Hughes, 2018; Gola, 2012). For example, Okumura and colleagues asked how early gaze-following and object processing relate to later language development (Okumura et al., 2017). In general, individual differences studies often focus on the relationship between social-cognitive abilities and: (1) family influences, (2) other cognitive constructs, and (3) social behavioral outcomes (for an overview, see Slaughter and Repacholi, 2003). Studies

on social-cognitive abilities and family influences include the effect of parenting practices (for a review, see Pavarini et al., 2013), attachment quality (e.g., Astor et al., 2020), mental state talk (Gola, 2012; Hughes et al., 2011; Lecce et al., 2014), and family background as parental education, occupation, sibling interaction and childcare (Bulgarelli & Molina, 2016; Cutting & Dunn, 1999; Dunn et al., 1991). Another group of individual differences studies focuses on the interplay of social and physical cognition (Herrmann et al., 2010), executive functions (Benson et al., 2013; Buttelmann et al., 2022; Carlson & Moses, 2001; Carlson et al., 2004; Hughes & Ensor, 2007), and language abilities (McEwen et al., 2007; Milligan et al., 2007; Okumura et al., 2017). Studies on social behavioral outcomes measured the interplay of social cognition and prosociality (for a review, see Imuta et al., 2016; Walker, 2005), stereotypes, resource allocations (Rizzo & Killen, 2018), and moral intentions (Sodian et al., 2016).

However, developmental psychologists are frequently surprised to find minor or no association between measures of social cognition that are thought to be theoretically related – cross-sectionally and/or longitudinally (e.g., Poulin-Dubois et al., 2023; Sodian, 2023; Sodian et al., 2016). This might be because traditional measures of social cognition are not designed to capture variation *between* children: they often rely on low trial numbers, small sample sizes, and dichotomous measures. A recent review showed that many studies on social cognition measures failed to report relevant psychometric properties at all (Beaudoin et al., 2020) or – when they did – showed mixed results on test-retest reliability (Hughes et al., 2000; Mayes et al., 1996).

To give an example: the most commonly applied prototypical measure for social cognition is the change-of-location false belief task (Baron-Cohen et al., 1985; Wimmer & Perner, 1983). Here, children watch a short sequence of events (often acted out or narrated by the experimenters). A doll called Sally puts her marble into a basket. After Sally leaves the scene, a second doll named Anne takes the marble and moves it into a box. Participants then get asked where Sally will look for her marble once she returns. The outcome measures false belief understanding in a dichotomous way: children pass the task if they take the protagonist's epistemic state into account and answer that she will look into the basket. Many years of research utilizing these verbal change-of-location tasks suggest that children develop belief-representing abilities at four to five years of age (for a review, see Wellman et al., 2001). Several cross-cultural studies supported this evidence (Barrett et al., 2013; Callaghan et al., 2005; cf. Mayer & Träuble, 2015).

However, from this age onwards, the change-of-location task shows ceiling effects and has very limited diagnostic value (Repacholi, 2003). Thus, this task seems well suited

to track a particular group-level developmental transition, yet it fails to capture individual differences (cf. “reliability paradox,” Hedge et al., 2018). As Wellman (2012) put it, “it’s really only passing/failing one sort of understanding averaged across age” (p. 317). This has profound implications for what studies on individual differences using this task (or others) can show. Poor measurement of social cognition on an individual level is likely to conceal relations between different aspects of cognition and may obscure developmental change. For example, Sodian et al. (2016) neither found a correlation between two moral Theory of Mind False Belief and Intention tasks at 60 months, nor a relationship between these two factors and implicit False Belief understanding at 18 months.

The “Sandbox task” is one of the few tasks that attempt to overcome these methodological challenges (Begeer et al., 2012; Bernstein et al., 2011; Coburn et al., 2015; Mahy et al., 2017; Sommerville et al., 2013). This continuous FB task measures the degree to which the estimate of another’s belief is biased by one’s own knowledge. Recent work questions the interpretation of this measure (Samuel et al., 2018a, b): it is unclear whether a smaller egocentric bias can be directly translated into a better mental state reasoning ability. Another evaluation criterion should, therefore, be whether a task captures meaningful variability in performance; that is, differences in test scores should correspond to differences in the social-cognitive ability in question.

Thus, developmental psychology faces a dilemma: many research questions rely on measuring individuals’ development, yet, there is a lack of tasks to measure these individual differences reliably. To capture the emergence of social-cognitive abilities and their relation to social factors in greater precision and detail, we must consequently address the methodological limitations of existing study designs (Hughes et al., 2011; Hughes & Leekam, 2004).

Schaafsma et al., (2015) compiled a “wish list” for new social-cognitive paradigms. They advocated for parametric – instead of dichotomous – measures covering proficiency as a range, avoiding floor and ceiling effects, and showing satisfactory test-retest reliability estimates (see also Beaudoin et al., 2020; Hughes & Devine, 2015). New tasks should capture variation across age groups, including older children and adults (Repacholi and Slaughter, 2003). Another goal in creating new tasks should be to focus on the “face value”: measures should probe the underlying social-cognitive ability as straight-forward and directly as possible. Keeping task demands minimal is also beneficial for using the paradigm in a variety of different cultural, clinical, and demographic contexts (Molleman et al., 2019). The task should serve as a proxy for behavior as it appears in the real world and should be validated in relation to real-world experiences (Repacholi and Slaughter, 2003).

## A new measure of gaze understanding

Our goal was to design a new measure of social cognition that captures individual differences across age groups in a systematic, reliable, and valid way. We focused on a fundamental ability implicated in many social-cognitive reasoning processes: gaze understanding – the ability to locate and use the attentional focus of an agent. The first component of this ability is often termed gaze following – turning one's eyes in the same direction as the gaze of another agent – and has been studied intensively (Astor et al., 2021; Byers-Heinlein et al., 2021; Coelho et al., 2006; Del Bianco et al., 2019; Frischen et al., 2007; Hernik & Broesch, 2019; Itakura & Tanaka, 1998; Lee et al., 1998; Moore, 2008; Shepherd, 2010; Tomasello et al., 2007). In our definition, gaze understanding goes one step further by including the *acting on the gaze-cued location* – therefore, using the available social information to guide one's behavior as needed in real-life conditions.

Following an agent's gaze provides insights into their intentions, thoughts, and feelings by acting as a “front end ability” (Brooks & Meltzoff, 2005, p. 535). Gaze is integral for many more sophisticated social-cognitive abilities, for example, inferences about knowledge states. As such, the eyes have been regarded as a “window into the mind” (Shepherd, 2010). Monitoring another's attention also supports building a common ground, which is important for action coordination and cooperative social interactions (Bohn & Köymen, 2018; Tomasello et al., 2007). In addition, gaze and language development seem to be related (Brooks & Meltzoff, 2005). Gaze facilitates word learning by helping to identify the referent of a new word and has been regarded as a crucial signal of nonverbal communication (Hernik & Broesch, 2019; Macdonald & Tatler, 2013).

While the emergence of gaze following has been well established, less is known about the developmental trajectory throughout childhood and adolescence. One possibility is that our social-cognitive ability in question is fully developed once emerged in infancy. However, many cognitive abilities continue to develop beyond early childhood (e.g., Gathercole et al., 2004 for working memory; Raviv & Arnon, 2018 for visual statistical learning). Therefore, children could potentially improve in understanding gaze, fine-tuning the performance of the already existing skill. Consequently, we aimed to assess the differentiation of the ability to understand gaze. Our goal was *not* to establish the youngest age at which children understand gaze cues. Rather, we wanted to examine how that ability changes with age. To accurately measure developmental change, we were interested in capturing individual variability.

To address the psychometric shortcoming of earlier work, we implemented the following design features: First,

we used a continuous measure which allowed us to capture fine-grained individual differences at different ages. Second, we designed short trials that facilitate more than a dozen replicates per subject. The result is more precise individual-level estimates. Third, we systematically investigated the psychometric properties of the new task.

Designing this task required a new testing infrastructure. We designed the task as an interactive web application. Previous research has successfully used online study implementations that compare well to in-person data collection (Bohn et al., 2021a, b; Frank et al., 2016). This greatly increased the flexibility with which we could modify the stimuli on a trial-by-trial basis. Furthermore, because the task is largely self-contained, it is much more controlled and standardized. Most importantly, it makes the task portable: testing is possible in-person using tablets but also remotely via the internet (no installation needed). As such, it provides a solid basis to study individual differences in gaze understanding across ages at scale. We make the task and its source code openly accessible for other researchers to use and modify.

## Task design

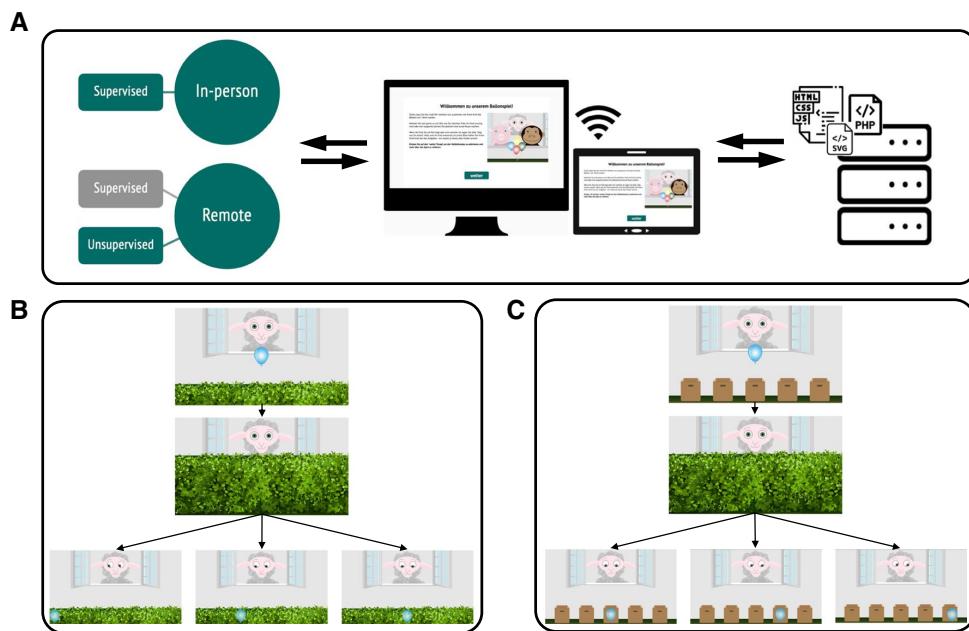
### Implementation

The code is open-source (<https://github.com/ccp-eva/tango-demo>), and a live demo version can be found under: <https://ccp-odc.eva.mpg.de/tango-demo/>.

The web app was developed using JavaScript, HTML5, CSS, and PHP. For stimulus presentation, a scalable vector graphic (SVG) composition was parsed. This way, the composition scales according to the user's viewport without loss of quality while keeping the aspect ratio and relative object positions constant. Furthermore, SVGs allow us to define all composite parts of the scene (e.g., pupil of the agent) individually. This is needed for precisely calculating the exact pupil and target locations and sizes. Additionally, it makes it easy to adjust the stimuli and, for example, add another agent to the scene. The web app generates two file types: (1) a text file (.json) containing metadata, trial specifications, and participants' click responses, and (2) a video file (.webm) of the participant's webcam recording. These files can either be sent to a server or downloaded to the local device. Personalized links can be created by passing on URL parameters.

### Stimuli

Our newly implemented task asks children and adults to search for a balloon. The events proceed as follows (see Fig. 1B and C). An animated agent (a sheep, monkey, or



**Fig. 1** Study setup. **A** Infrastructure for online testing. (i) Subjects aged 3 to 99+ can participate. Data collection can take place anywhere: online, in kindergartens, or in research labs. (ii) The task is presented as a website that works across devices. (iii) The scripts for the website and the recorded data are stored on secure in-house servers. **B** Hedge version (continuous) of the TANGO. (i) The agent stands in a window with the target in front of them. (ii) A hedge grows and covers the target. (iii) The target falls to a random loca-

tion on the ground. The agent's eyes track the movement of the target. Three exemplary target locations are shown to depict how indicative the agent's gaze cues are in determining the target's location. The transparent target is only shown for an illustrative purpose (not visible during the test). **C** Box version (discrete) of the TANGO. Number of boxes (min. 1; max. 8) as potential hiding locations can be set according to the researcher's need

pig) looks out of a window of a house. A balloon (i.e., target; blue, green, yellow, or red) is located in front of them. The target then falls to the ground. At all times, the agent's gaze tracks the movement of the target: the pupils and iris move so that their center aligns with the center of the target. While the distance of the target's flight depends on the final location, the target moves at a constant speed. Participants are then asked to locate the target: they respond by touching or clicking on the screen. Visual access to the target's true location is manipulated by a hedge. Participants either have full, partial, or no visual access to the true target location. When partial or no information about the target location is accessible, participants are expected to use the agent's gaze as a cue.

To keep participants engaged and interested, the presentation of events is accompanied by cartoon-like effects. Each trial starts with an attention-getter: an eye-blinking sound plays while the pupils and iris of the agent enlarge (increase to 130%) and change in opacity (decrease to 75%) for 0.3 s. The landing of the target is accompanied by a tapping sound. Once the target landed, the instructor's voice asked "Where is the balloon?". To confirm the participant's click, a short

plop sound plays, and a small orange circle appears at the location of choice. Participants do not receive differential feedback so that learning effects are reduced, and trials stay comparable across the sample. If no response is registered within 5 s after the target landed, an audio prompt reminds the participant to respond.

### Trials

Trials differ in the amount of visual access that participants have to the final target position. Before the test trials start, participants complete four training trials during which they familiarize themselves with touching the screen. In the first training trial, participants have full visual access to the target flight and the target's end location and are simply asked to click on the visible balloon. In the second and third training trials, participants have partial access: they witness the target flight but cannot see the target's end location. They are then asked to click on the hidden balloon, i.e., the location where they saw the target land. In test trials, participants have no visual access to the target flight or the end location. Participants are expected to use the agent's gaze as a cue

to locate the target. The first trial of each type comprises a voice-over description of the presented events. The audio descriptions explicitly state that the agent is always looking at the target (see Supplements for audio script). After the four training trials, participants receive 15 test trials. The complete sequence of four training trials and 15 test trials can be easily completed within 5–10 min.

### **Study versions**

We designed two study versions that differ in the target's final hiding place and, consequently, in the outcome measure: a *hedge version* (continuous) and a *box version* (discrete). Both versions use the same first training trial and then differ in the consecutive training and test trials. In the hedge version, participants have to indicate their estimated target location directly on a hedge. Here, the dependent variable is imprecision, which is defined as the absolute difference between the target center and the *x* coordinate of the participant's click. In the box version, the target lands in a box, and participants are asked to click on the box that hides the target. Researchers can choose how many boxes are shown: one up to eight boxes can be displayed as potential hiding locations. Here, we use a categorical outcome (i.e., which box was clicked) to calculate the proportion of correct responses. Note that in the test trials of both versions, the target flight is covered by a hedge. In the hedge version, the hedge then shrinks to a minimum height required to cover the target's end location. In the box version, the hedge shrinks completely. The boxes then hide the target's final destination (see Fig. 1B and C).

### **Randomization**

All agents and target colors appear equally often and are not repeated in more than two consecutive trials. The randomization of the target end location depends on the study version. In the hedge version, the full width of the screen is divided into ten bins. Exact coordinates within each bin are then randomly generated. In the box version, the target randomly lands in one of the boxes. As with agent and color choice, each bin/box occurs equally often and can only occur twice in a row.

### **Individual differences**

Our first aim was to assess whether the TANGO captures inter-individual variation in a child and adult sample. Furthermore, we were interested in whether and how the data collection mode (in-person vs. remote) influences responses. Since we expected a greater difference in responses between

the two data collection modes for children, the analysis of data collection mode was restricted to a child sample.

Task design, data collection, and sample sizes were pre-registered: <https://osf.io/snju6> (child sample) and <https://osf.io/r3bhn> (adult sample). The analyses reported here were not pre-registered but followed the structure of the ones specified in the above pre-registrations (see Footnotes for deviations). The additional analyses mentioned in the pre-registrations (e.g., computational model) address separate research questions (e.g., process-level account of gaze understanding) and will be reported elsewhere. In this paper, we focus on the methodological and psychometric aspects of our task.

The study design and procedure obtained ethical clearance by the MPG Ethics commission Munich, Germany, falling under a packaged ethics application (Appl. No. 2021\_45), and was approved by an internal ethics committee at the Max Planck Institute for Evolutionary Anthropology. The research adheres to the legal requirements of psychological research with children in Germany.

Participants were equally distributed across the two study versions. Data were collected between May and October 2021.

### **Participants**

We collected data from an in-person child sample, a remote child sample, and a remote adult sample. In-person testing with children took place in kindergartens in Leipzig, Germany. The in-person child sample consisted of 120 children, including 40 3-year-olds (mean = 41.45 months, SD = 3.85, range = 36–47, 22 girls), 40 4-year-olds (mean = 54.60 months, SD = 3.10, range = 48–59, 19 girls), and 40 5-year-olds (mean = 66.95 months, SD = 3.39, range = 60–71, 22 girls).

We pre-registered the replacement for participants that finished fewer than four test trials. This was not the case for any participant. One child stopped participation after 12 test trials but was included in the sample due to the pre-registered replacement rule. Two additional participants were recruited but not included in the study because the participant did not feel comfortable interacting with the tablet alone ( $n = 1$ ), or due to an originally miscalculated age of the child ( $n = 1$ ).

For our remote child sample, we recruited families via an internal database of children living in Leipzig, Germany, whose parents volunteered to participate in child development studies and who indicated an interest in online studies. Families received an email with a short study description and a personalized link. If they had not participated in the study within 2 weeks, they received a reminder via e-mail. The response rate to invitations after the reminder was ~ 50%.

The remote child sample included 147 children, including 45 3-year-olds (mean = 42.62 months, SD = 3.35, range = 36–47, 14 girls), 47 4-year-olds (mean = 52.64 months, SD = 3.40, range = 48–59, 25 girls), and 55 5-year-olds (mean = 65.11 months, SD = 3.77, range = 60–71, 27 girls). Of these, three families participated twice. In these cases, we only kept the data sets from the first participation.

Four additional participants were recruited but not included in the study because they were already part of the in-person kindergarten sample ( $n = 3$ ), or because of unknown age ( $n = 1$ ).

Please note that we did not collect participant-specific demographics. In the following, we aim to provide context and generalizations based on the broader community and the larger pool of potential participants. Children in our sample grow up in an industrialized, urban Central-European context in a city with approximately 600,000 inhabitants. They often live in nuclear two-generational families with few household members. Information on socioeconomic status was not formally recorded, although the majority of families come from mixed, mainly mid to high socioeconomic backgrounds with high levels of parental education. The median individual monthly net income in the year 2021 was ~ 1,600€ for the city of Leipzig.

Adults were recruited via *Prolific* (Palan & Schitter, 2018). *Prolific* is an online participant recruitment service with a predominantly European and US-American subject pool. One hundred English speakers with an average age of 31.34 years (SD = 10.77, range = 18–63, 64 females) were included. Participants live in a variety of different countries: the UK, Italy, Spain, Poland, Netherlands, Canada, Australia, Ireland, South Africa, Norway, Portugal, France, Austria, Finland, Greece, Germany, the U.S., Mexico, Chile, Iceland, New Zealand, Czech Republic, Hungary, Latvia, and Switzerland. In this sample, most participants resided in the United Kingdom ( $n = 47$ ), South Africa ( $n = 8$ ), and Portugal ( $n = 6$ ). Additional detailed information can be found in the data set online. For completing the study, subjects were paid above the fixed minimum wage (on average £10.00 per hour; see Supplements for further detail).

## Procedure

Children in our in-person sample were tested on a tablet in a quiet room in their kindergarten. An experimenter guided the child through the study.

Children in the remote sample received a personalized link to the study website, and families could participate at any time or location. At the beginning of the online study, families were invited to enter our “virtual institute”. We welcomed them with a short introductory video of the study leader, describing the research background and

further procedure. Then, caregivers were informed about data security and were asked for their informed consent. They were asked to enable the sound and seat their child centrally in front of their device. Before the study started, families were instructed on how to set up their webcam and enable the recording permissions. We stressed that caregivers should not help their children. Study participation was video recorded whenever possible in order to ensure that the children themselves generated the answers. Depending on the participant’s device, the website automatically presented the hedge or box version of the study. For families that used a tablet with a touchscreen, the hedge version was shown. Here, children could directly click on the touchscreen to indicate where the target is. For families that used a computer without a touchscreen, the website presented the box version of the task. We assumed that younger children in our sample would not be acquainted with using a computer mouse. Therefore, we asked children to point to the screen, while caregivers were asked to act as the “digital finger” of their children and click on the indicated box.

All participants received 15 test trials. In the box version, we decided to adjust the task difficulty according to the sample: children were presented with five boxes, while adults were presented with eight boxes as possible target locations.

## Analysis

All test trials without voice-over descriptions were included in our analyses. We ran all analyses in R version 4.3.0 (2023-04-21) (R Core Team, 2022). Regression models were fitted as Bayesian generalized linear mixed models (GLMMs) with default priors for all analyses, using the function `brm` from the package `brms` (Bürkner, 2017, 2018).

To estimate the developmental trajectory of gaze understanding and the effect of data collection mode, we fit a GLMM predicting the task performance in each trial by age (in months, z-transformed) and data collection mode (reference category: in-person supervised). The model included random intercepts for each participant and symmetric target position, and a random slope for symmetric target position within participants (model notation in R: `performance ~ age + datacollection + symmetricPosition + trialNr + (1 + symmetricPosition + trialNr | subjID)`).<sup>1</sup>

<sup>1</sup> In the pre-registration (<https://osf.io/snju6>), we specified the following model structure: “All models will include a fixed effect of target centrality and age, a random intercept for ID and a random slope for trial number by ID. For both study versions, we will compare the above specified null models with a model including data source (live vs. online) as a fixed effect.” Or, in R model formula: R: `performance ~ target_centrality + age + (1 | ID) + (1 + trial | ID)`. In this paper, we added `symmetricPosition` (synonymous to `target_centrality`) as a random slope because we expected that this item effect could vary between participants. To be better able to interpret trial

Here, symmetricPosition refers to the absolute distance from the stimulus center (i.e., smaller value meaning more central target position). We expected that trials could differ in their difficulty depending on the target centrality and that these item effects could vary between participants.

For the hedge version, performance was defined as the absolute click distance between the target center and the click x coordinate, scaled according to target widths, and modeled by a lognormal distribution. For the box version, the model predicted correct responses (0/1) using a Bernoulli distribution with a logit link function. We inspected the posterior distribution (mean and 95% credible interval (CrI)) for the age and data collection estimates.

## Results

Children showed nearly perfect precision in the first training trial. As visual access to the target location decreased in the subsequent training trials, imprecision levels increased (see Supplements). Within test trials, children's imprecision levels did not vary as a function of trial number. We take this as evidence that (A) children were comfortable touching the screen, (B) children understood the task instructions insofar as they aimed at locating the target, and (C) our experimental design successfully manipulated task difficulty.

We found a strong developmental effect: with increasing age, participants got more accurate in locating the target. In the hedge version, children's click imprecision decreased with age, while in the box version, the proportion of correct responses increased (see Fig. 2A and F). Most participants in the box version performed above chance level. By the end of their sixth year of life, children came close to the adult's proficiency level. Most importantly, however, we found substantial inter-individual variation across study versions and age groups. For example, some 3-year-olds were more precise in their responses than some 5-year-olds. Even though variation is smaller, we could even find inter-individual differences in the adult sample.

As Fig. 2A and F show, our remotely collected child data resembled the data from the kindergarten sample. We found evidence that responses of children participating remotely were slightly more precise. This difference was mainly driven by the younger participants and was especially prominent in the box version of the task. It is conceivable that caregivers were especially prone to influence the behavior of younger children. In the box version, caregivers might

have had more opportunities to interfere since they carried out the clicking for their children.<sup>2</sup>

Our GLMM analysis corroborated the visual inspection of the data: in the hedge version, the estimates for age ( $\beta = -0.32$ ; 95% CrI [-0.41; -0.23]) and data collection mode  $-0.31$  (95% CrI [-0.48; -0.14]) were negative and reliably different from zero. In the box version, the estimate of age ( $\beta = 0.68$  (95% CrI [0.44; 0.93])) and the estimate of data collection mode ( $\beta = 1.10$  (95% CrI [0.66; 1.56])) were positive and reliably different from zero. Note that even though confidence intervals from the data collection estimates were wide, the effect was positive and reliably different from zero in that our remote sample performed more accurately than our in-person sample.

There was no effect of trial number (hedge version:  $\beta = 0.00$ ; 95% CrI [-0.02; 0.01]; box version:  $\beta = -0.02$ ; 95% CrI [-0.05; 0.01]). However, trials differed in difficulty depending on where the target landed (hedge version:  $\beta = 0.47$ ; 95% CrI [0.40; 0.54]; box version:  $\beta = -1.59$ ; 95% CrI [-1.88; -1.31]). When the target landed closer to the center of the screen, participants were more accurate in locating it.

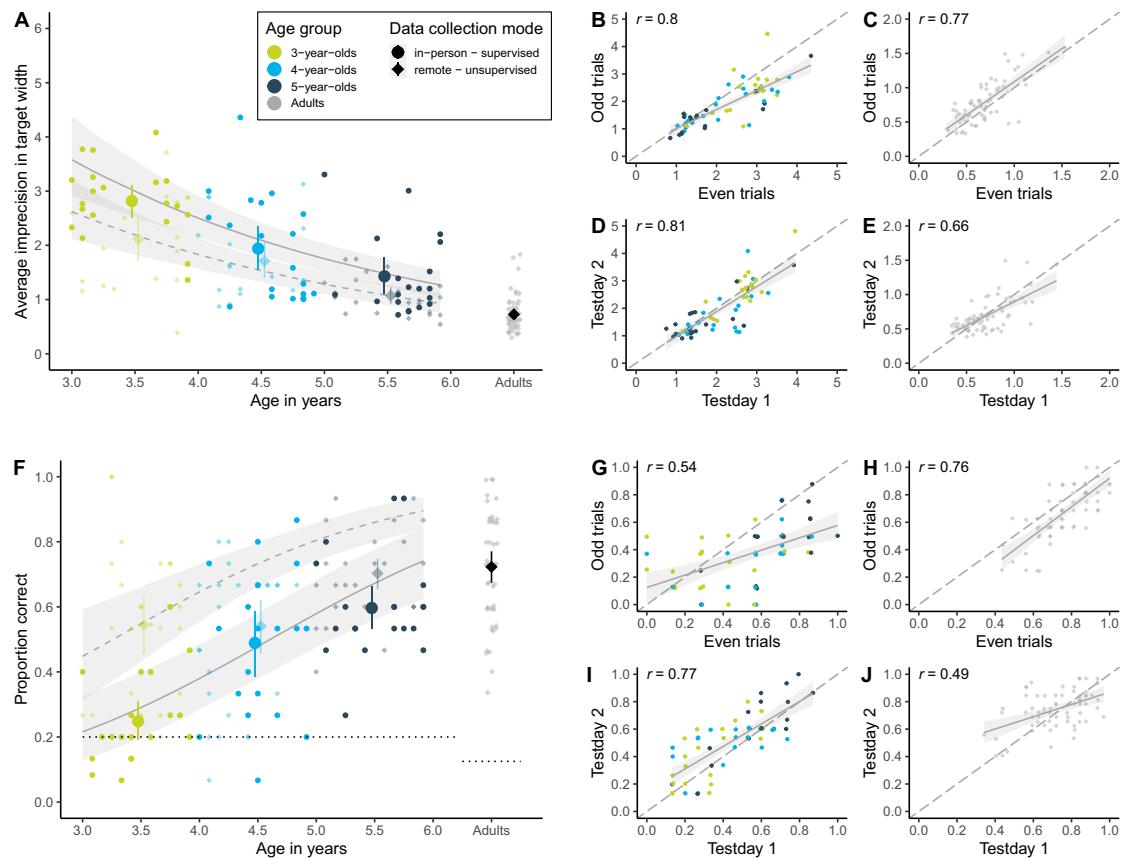
## Discussion

Our task measured inter-individual differences in both children and adults; that is, we found substantial variation in individuals across age groups. For example, some 3-year-olds showed greater precision levels than some 5-year-olds. This holds across both study versions. However, due to the continuous study design, the hedge version was able to capture more fine-grained differences in individual performance. We see substantial developmental gains: with increasing age, participants became on average more and more precise in locating the target. The 5-year-olds reached a proficiency level close to the adults' level. For neither study version nor age group did we find any floor or ceiling effects. The presentation as a web app with cartoon-like features kept children interested and motivated throughout the 15 test trials. Furthermore, we found a comparable developmental trajectory for an unsupervised remote child sample. This illustrates the flexibility of the task design.

Footnote 1 (continued)

number effects, we decided to include it as a fixed effect. Data collection mode (formerly named "data source") proved as a meaningful predictor and was accordingly added to the model.

<sup>2</sup> In an exploratory analysis, we coded parental behavior and environmental factors during remote unsupervised testing. We focused on the subsample with the greatest performance difference between data collection modes: the 3-year-olds in the box version of the task ( $n = 16$ ). We reasoned that if parental interference cannot explain the greatest performance difference in our sample, the effects would be negligible in the remaining sample. Based on our model comparison, we conclude that there is no clear evidence of a stable effect of parental interference. See Supplements for further detail.



**Fig. 2** Measuring inter-individual variation. **A** Developmental trajectory in the continuous hedge version. Performance is measured as imprecision, i.e., the absolute distance between the target's center and the participant's click (averaged across trials). The unit of imprecision is counted in the width of the target, i.e., a participant with imprecision of 1 clicked on average one target width to the left or right of the true target center. **B** Internal consistency (odd-even split) in hedge child sample. **C** Internal consistency in hedge adult sample. **D** Test-retest reliability in hedge child sample. **E** Test-retest reliability in hedge adult sample. **F** Developmental trajectory in the discrete box version. Performance is measured as the proportion of correct responses, i.e., how many times the participant clicked on the box that contained the target. The dotted black line shows the level of performance expected by chance (for child sample 20%, i.e., one out of five boxes; for adult sample 12.5%, i.e., one out of eight boxes). **G** Internal consistency (odd-even split) in box child sample. **H** Internal

consistency in box adult sample. **I** Test-retest reliability in box child sample. **J** Test-retest reliability in box adult sample. For (A) and (F), regression lines show the predicted developmental trajectories (with 95% Crl) based on GLMMs, with the *line type* indicating the data collection mode. Large points with 95% CI (based on non-parametric bootstrap) represent performance means by age group (binned by year). Small points show the mean performance for each subject averaged across trials. For adult data in (A) and (F), we added minimal horizontal and vertical noise to avoid overplotting. The shape of data points represents data collection mode: opaque circles for in-person supervised data collection and translucent diamonds for remote unsupervised data collection. The color of data points denotes age group. For (B–E) and (G–J), regression lines with 95% CI show smooth conditional mean based on a linear model (generalized linear model for box version), with Pearson's correlation coefficient  $r$

### Internal consistency and test-retest reliability

As a next step, we aimed to investigate whether the variation that we captured with the TANGO is reliable. We assessed internal consistency (as split-half reliability) and test-retest reliability. Task procedure, data collection, and sample sizes

were pre-registered (<https://osf.io/xqm73> for the child sample and <https://osf.io/nu62m> for the adult sample). Participants were equally distributed across the two study versions. Data was collected between July 2021 and June 2022.

The study design and procedure obtained ethical clearance by the MPG Ethics commission Munich, Germany, falling under a packaged ethics application (Appl.

No. 2021\_45), and was approved by an internal ethics committee at the Max Planck Institute for Evolutionary Anthropology. The research adheres to the legal requirements of psychological research with children in Germany.

## Participants

Participants were recruited in the same way as in the previous study. The child sample consisted of 120 children, including 41 3-year-olds (mean = 42.34 months, SD = 3.10, range = 37–47, 20 girls), 41 4-year-olds (mean = 53.76 months, SD = 3.15, range = 48–59, 21 girls), and 38 5-year-olds (mean = 66.05 months, SD = 3.40, range = 60–71, 19 girls).

Additional 65 children were recruited but not included in the analysis due to absence on the second test day ( $n = 49$ ), canceled testing because of COVID-19 cases in the kindergarten ( $n = 7$ ), children did not want to participate a second time ( $n = 5$ ), children already participated in the first data collection round and were included in the above-mentioned *Individual Differences* sample ( $n = 3$ ), or children did not understand the task instructions ( $n = 1$ ; manifested in too early clicking in the training trials while the instructions were still playing, and no clicking by themselves in the test trials). Two additional children were recruited for the first day (as backup) in case another child would be absent on the second test day. Similar to our first study, we did not collect participant-specific demographics. For a community-based description of our participant pool, see Participant section of the first study.

As in our first study, adults were recruited via *Prolific* (Palan & Schitter, 2018). The adult sample included 136 English speakers with an average age of 25.73 years (SD = 8.09, range = 18–71, 87 females; see Supplements for further details). Most participants resided in South Africa ( $n = 48$ ), the United Kingdom ( $n = 19$ ), and the United States ( $n = 14$ ). See Supplements and the available online data set for more detailed information.

## Procedure

We applied the same procedure as in the first study, with the following differences. Participants completed the study twice, with a delay of  $14 \pm 3$  days. The target locations, as well as the succession of agents and target colors, were randomized once and then held constant across participants. The child sample received 15 test trials. In the hedge version, each bin occurred once, making up ten of the test trials. For the remaining five test trials, we repeated one out of two adjacent bins (i.e., randomly chose between bins 1 & 2, bins 3 & 4, etc.). In the box version, we ensured that each of the five boxes occurred exactly three times during

test trials. Adults in the hedge version received 30 test trials, each of the ten bins occurring exactly three times. Adults in the box version received 32 test trials, with each of the eight boxes occurring exactly four times. For the four training trials, we repeated a fixed order of random bins/boxes. For the adult sample, we decided to increase the number of trials in order to get more accurate reliability estimates. Trial numbers were multipliers of the possible target locations and therefore differed between hedge and box versions. For the child sample, we stuck to the same number of trials to not risk higher attrition rates.

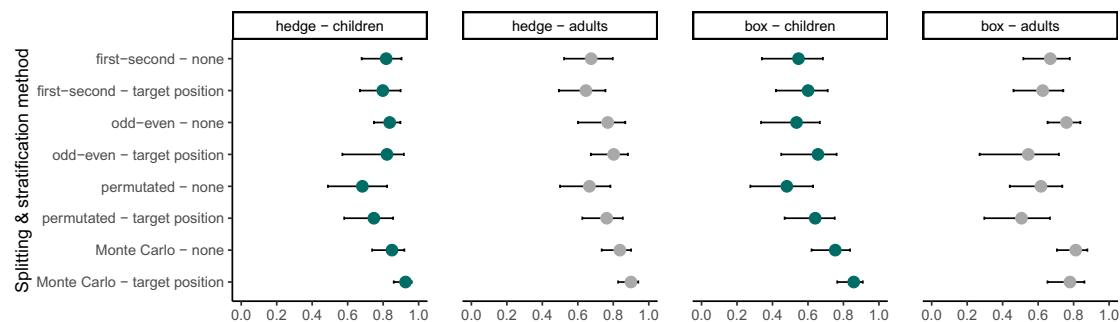
## Analysis

We assessed reliability in two ways. First, we focused on internal consistency by calculating split-half reliability coefficients.<sup>3</sup> For each subject, trials were split into odd and even trials. Performance was aggregated and then correlated using Pearson correlation coefficients. For this, we used the data of the first test day. Performance was defined according to each study version: in the hedge version, performance referred to the mean absolute difference between the target center and the click coordinate, scaled according to target widths; in the box version, we computed the mean proportion of correct choices.

Pronk et al., (2022) recently compared various methods for computing split-half reliability that differ in how the trials are split into parts and whether they are combined with stratification by task design. To compare our traditional approach of a simple odd-even split, we additionally calculated split-half reliability estimates using first-second, odd-even, permuted, and Monte Carlo splits without and with stratification by target position. First-second and odd-even splits belong to single sample methods since each participant has a single pair of performance scores, while permuted (without replacement) and Monte Carlo (with replacement) splits make use of resampling. Analyses were run using the function `by_split` from the `splithfr` package (Pronk et al., 2021).

Second, we assessed test-retest reliability. We calculated performance scores (depending on the study version as described above) for each participant in each test session and correlated them using Pearson correlation coefficients. Furthermore, for our child sample, we report an age-corrected correlation between the two test days using a GLMM-based approach (Rouder & Haaf, 2019). We fit trial-by-trial data with a fixed effect of age, a random intercept for each subject, and a random slope for test day (model notation

<sup>3</sup> The assessment of internal consistency was not pre-registered and was included as an additional measure of reliability.



**Fig. 3** Internal consistency. Reliability coefficients per splitting method, stratification level, study version, and age group. Error bars show the 95% confidence intervals of the coefficient estimates, calculated with the function by\_split from the splithalfr package (Pronk et al., 2021)

in R: performance ~ age + (0 + relday | subID)). For the hedge version, performance was modeled by a lognormal distribution, while the model for the box version used a Bernoulli distribution with a logit link function. The model computes a correlation between the participant-specific estimates for each test day. This can be interpreted as the test-retest reliability. By using this approach, we do not need to compromise on data aggregation and, therefore, loss of information. Since the model uses hierarchical shrinkage, we obtain regularized, more accurate person-specific estimates. Most importantly, the model includes age as a fixed effect. The correlation between the two person-specific estimates is consequently the age-independent estimate for test-retest reliability. This rules out the possibility that a high correlation between test days arises from domain-general cognitive development instead of study-specific inter-individual differences. A high correlation between our participant-specific model estimates would indicate a high association between test days.

## Results

We found that the TANGO measured systematic variation: split-half and test-retest reliability was medium to high. For internal consistency, we show traditional odd-even splits on our data and the corresponding Pearson correlation coefficients in Fig. 2B, C, G, and H.

Figure 3 compares split-half reliability coefficients by splitting and stratification method (Pronk et al., 2021). In the hedge version, the split-half reliability coefficients ranged from 0.65 to 0.93. In the box version, split-half reliability coefficients ranged from 0.48 to 0.86. Similar to the results of Pronk et al. (2021), we found that more robust splitting methods that are less prone to task design or time confounds yielded higher reliability coefficients. In most cases, stratifying by target position led to similar or even higher estimates compared to no stratification. As expected, we found higher

coefficients for the samples with higher variation, i.e., for our continuous hedge version of the task.

For test-retest reliability, we show the association between raw performance scores of the two test days and corresponding Pearson correlation coefficients in Fig. 2D, E, I and J.<sup>4</sup> See Supplements for reliability estimates by age group.

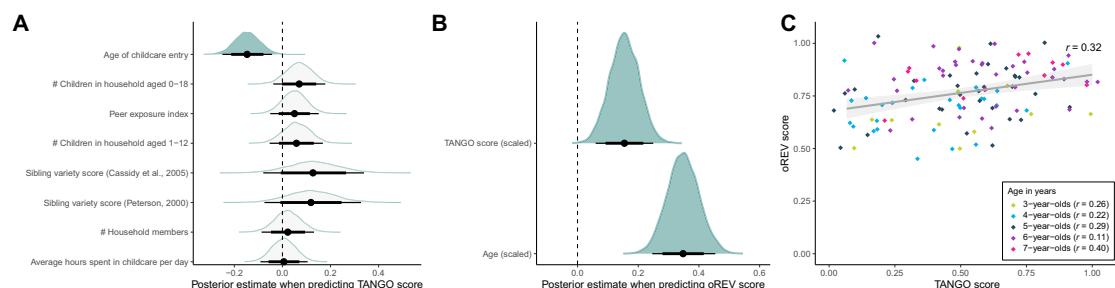
The age-corrected, GLMM-based retest reliabilities for children yielded similar results. In the hedge version, the correlation between test days was 0.89 (95% CrI [0.64;1.00]). In the box version, the correlation between test days was 0.91 (95% CrI [0.70;1.00]).

For both study versions, reliability estimates based on the GLMM approach were higher than the Pearson correlations. The GLMM-based estimates are less noisy due to the fact that the model uses all available information (e.g., participant age) and does not rely on data aggregation across trials.

## Discussion

Our results indicated that the measured variation was systematic. As expected, the continuous measure of the hedge version yielded higher reliability estimates than the discrete box version. For children, the model-based reliability estimates showed that the task did capture individual differences even when correcting for age. This corroborates what we already saw in Fig. 2: there was a clear overlap between age groups, indicating that age is predictive of performance for the mean but is not the main source of individual differences.

<sup>4</sup> In the hedge version, we excluded one 3-year-old, one 5-year-old, and two adults from the test-retest analysis. The performance of the mentioned participants was 3 standard deviations above/below the mean of each sample. Including the two children yielded a Pearson correlation coefficient of  $r = 0.88$ . Including the two adults yielded a Pearson correlation coefficient of  $r = 0.73$ .



**Fig. 4** Validity of the TANGO. **A** Influence of social-environmental factors on gaze understanding. **B** Influence of gaze understanding on receptive vocabulary. For (A) and (B), the graphs show the posterior distributions for the respective predictor of each model. *Filled green density curves* show that adding the respective predictor improved the model fit compared to the null model. *Black dots* represent means, *thicker black lines* 80% CrI and *thinner black lines* 95% CrI. The oREV score is the proportion of correctly selected pictures in

the receptive vocabulary task. Similarly, the TANGO score refers to proportion of correctly located targets (see Supplements for further detail). **C** Influence of gaze understanding on receptive vocabulary by age. The *regression line* with 95% CI shows a smooth conditional mean based on a generalized linear model, with *Pearson's correlation coefficient r*. *Dots* show the mean performance for each subject averaged across trials with minimal horizontal and vertical noise added to avoid overplotting. The *color of dots* denotes age group

## Validity

After having probed our new testing infrastructure and the psychometric properties of the TANGO, we aimed at establishing its validity. One way to assess validity is to correlate the social-cognitive ability in question to concepts that are thought to be theoretically related. Social cognition is often described as developing in response to social interaction (Devine & Hughes, 2018; Hughes & Leekam, 2004). It is assumed that opportunities to play, communicate and argue with peers help children to understand the human mind. Therefore, many studies link social cognition to opportunities for social interaction captured in demographic variables such as parent-child interaction quality and quantity, mental state talk, and center-based childcare (Bulgarelli & Molina, 2016; Dunn et al., 1991; Pavarini et al., 2013). In particular, family constellation, the number and age of siblings, and their interaction have been linked to social cognition (Cassidy et al., 2005; Dunn et al., 1991; Perner et al., 1994; Peterson, 2000; Zhang et al., 2021).

To assess such external validity for the TANGO, we handed out a brief demographic questionnaire to families of our kindergarten and online child sample and asked for (1) the total number of household members, (2) the number of children, (3) age of the other children, (4) whether the child was in daycare, and if yes, (5) since when and (6) for how long on an average day. 109 families filled out the questionnaire and were included in the analysis. We used parents' responses to construct different scores suggested in the literature (Cassidy et al., 2005; Peterson, 2000), capturing aspects of children's opportunities for social interaction with adults and peers. Only the predictor "age of childcare entry" improved the model fit compared to the null model (see Fig. 4A; for model comparisons, see Supplements): the older the children were when entering

childcare, the less likely they were to correctly use the available gaze cue. Figure 4A shows that all other predictor scores were positively linked to gaze understanding. Effect sizes were probably influenced by the lack of variance in the predictors: variables like household size and number of siblings typically vary very little among German households (see Supplements for distribution characteristics of the predictors). Albeit the effects were weak, they are consistent with the literature.

In addition, children's sensitivity to gaze has been linked to language acquisition (Brooks & Meltzoff, 2005; Del Bianco et al., 2019; Okumura et al., 2017). Discovering the attentional focus of your counterpart is thought to facilitate word learning, for example by identifying the referent of a new word (Tomasello, 2003). For 117 children, we also collected data with a receptive vocabulary test (oREV; Bohn et al., 2023) approximately 6 months (mean = 0.52 years, SD = 0.08, range = 0.06–0.80) after their participation in the TANGO. In the oREV task, children are shown four pictures (see Supplements for further detail) and hear a verbal prompt asking them to select one of the pictures. The oREV score is the proportion of correctly selected pictures. We found a substantial relationship between gaze understanding 6 months prior and receptive vocabulary, even when correcting for age (see Fig. 4B and C). Taken together, our newly developed task shows connections to external variables and psychological constructs that are characteristic of measures of social cognition.

## General discussion

We have presented a new experimental paradigm to study gaze understanding across the lifespan. This paper contributes to methodological advances in developmental

psychology in the following ways: first, we captured fine-grained individual differences in gaze understanding at different ages – from early childhood until adulthood. Individuals behaved consistently differently from one another (i.e., we found substantial variation between individuals across age groups). Second, our task showed satisfactory psychometric properties with respect to internal consistency and test-retest reliability estimates. Third, our new browser-based testing infrastructure ensures standardized, portable data collection at scale, both remotely as well as in person. In sum, the TANGO provides a step toward more robust and reliable research methods, especially with regard to measuring developmental change in a fundamental social-cognitive ability. The web app (<https://ccp-odc.eva.mpg.de/tango-demo/>) and its source code (<https://github.com/ccp-eva/tango-demo>) are freely accessible for use and modification.

Our continuous measure of children's gaze understanding moves away from treating a social-cognitive ability as an all-or-nothing matter (e.g., dichotomous measures in pass/fail situations) toward an ability on a continuum (Beaudoin et al., 2020; Hughes & Devine, 2015). Identifying variability in social-cognitive abilities is vital for accurately quantifying developmental change, revealing relations between different aspects of cognition and children's real-life social surroundings, and for meaningful comparisons across human cultures and across animal species. Dedicated measures of individual differences will help us to design meaningful interventions and progress in psychological theory building (Hedge et al., 2018).

Our continuous hedge version yields higher internal consistency estimates than the categorical box version. Both study versions exhibit high test-retest reliability, also when controlling for age. Therefore, when a sufficient number of trials is presented, the box version of the task can also yield reliable individual estimates (cf. Hughes et al. (2000); improved reliability through aggregation). When testing time is limited (and the number of trials might be low), we recommend using the continuous study version for higher internal consistency. However, the categorical box version demonstrates design features that might be preferable in some research contexts: for example, researchers could induce different levels of salience for each box. Our task could consequently be used to study bias, preferences, and diverse desires (e.g., matching the box appearance to some feature/behavioral characteristic of the agent).

In the split-half reliability calculations, the more accurately the statistical method represents the task structure, the higher the reliability estimates are. Therefore, we argue that future research should aim at implementing statistical analyses that mirror the complexity of the experimental design. Theoretically informed, computational cognitive models are a promising approach forward (Haines et al.,

2020). Computational models take advantage of all available information and model variation between and within individuals in an even more fine-grained and psychologically interpretable manner. Computational frameworks could also be used to model performance and their underlying cognitive processes across tasks. With nested hierarchical models, we could assess the systematic relation between various social-cognitive abilities and recover potentially shared structures between cognitive processes (Bohn et al., 2023).

The TANGO fulfills several demands that were proposed by Schaafsma et al. (2015)'s wish list: it measures proficiency on a continuum, avoids floor and ceiling effects, measures variation across age ranges, shows satisfactory reliability estimates, and has a high face value.

In addition to the new task design itself, we designed a new testing infrastructure. The TANGO is presented as an interactive web app. This enables presentation across devices without any prior installation. Stimuli presentation is achieved through the use of SVGs. This has several advantages: the aspect ratio and stimulus quality are kept constant no matter which size the web browser displays. The cartoon-like presentation makes the task engaging for children and adults alike. Most importantly, we can dynamically modify the stimulus details (e.g., target positions) on a trial-by-trial basis. Presented agents, voice-over instructions, and objects can be easily adapted for future task modifications or specific linguistic and cultural settings.

The browser-based implementation allows for different data collection modes: participants can be tested in person with supervision or remotely at home. Test instructions are standardized, and with prior informed consent, the webcam records study participation. This allows us to scale up data collection: testing is flexible, fast, and requires no further experimenter training. We compared children participating in-person and supervised in kindergartens with children who participated remotely at home. Our results suggest a comparable developmental trajectory of gaze understanding in both samples. Children in the remote sample were slightly more precise. This effect was most pronounced in the 3-year-olds in the box version (for an analysis of the webcam recordings, see Supplements). Therefore, we recommend using a tablet for remote data collection. Children can click for themselves, and caregivers have less chance to interfere. The design choices of the infrastructure underline how our study design can act as a versatile framework for addressing further research questions on social-cognitive development.

With respect to validity, we found that performance in the TANGO was related to relevant external variables and cognitive measures. Family-level variables, capturing a child's opportunity for social interaction, systematically influenced gaze understanding. Even though the effects

were small and confidence intervals were wide, it is remarkable that we were able to detect relationships between this fundamental social-cognitive ability and very distant, real-life variables. In addition, we assessed the influence of gaze understanding on receptive vocabulary. We found a substantial relationship between the two variables, even when correcting for age. Taken together, this speaks to the validity of the TANGO.

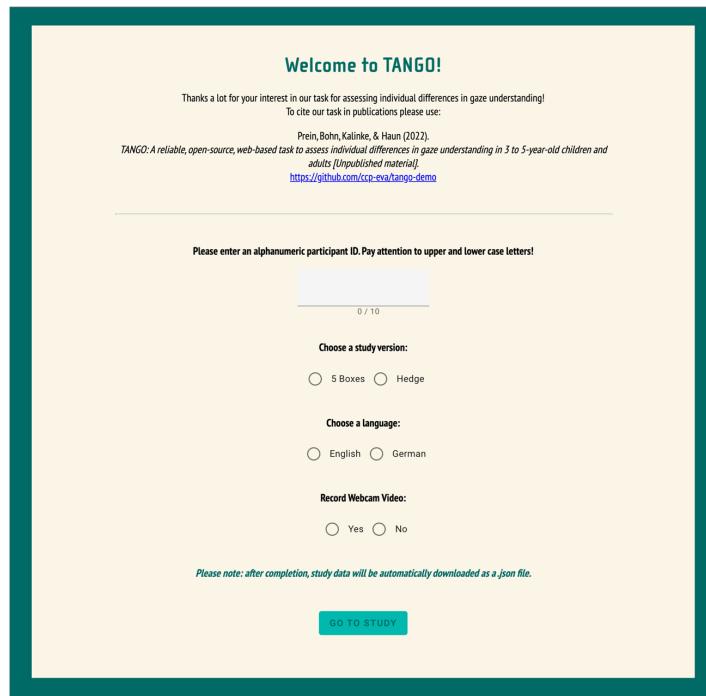
### Limitations

First, we want to address the scope and interpretation of the TANGO. We believe that solving the task requires locating the attentional focus of an agent as the gaze cues the target location. This speaks to the face validity of the TANGO and its focus on an inherently social stimulus. However, we do not want to claim that the TANGO does not also recruit other, domain-general processes. For example, we believe that a considerable part of gaze understanding relies on vector-following: not just in our task but also in real life. From that perspective, gaze understanding could be seen as a particular case of vector-following that is learned and used in social interactions. Future research could assess how

much variation of the gaze understanding task is shared with a physical vector-following task. In addition, computational cognitive models might prove helpful in defining children's behavior on a process-level and disentangling parameters that influence task performance (e.g., spatial acuity).

Second, the influence of testing modality requires further attention. Remote data collection loosens the standardization of the experimental procedure, as we cannot prevent caregivers from interfering. Steering the child's behavior becomes less possible when touchscreens are used, and the child can click on the screen directly. This is why we recommend using tablets for remote data collection. However, it should be noted that families' access to technological devices varies, both across socio-environmental as well as cultural settings.

Third, the children in our sample live in an industrialized, urban Central-European context. It is unclear how our results would generalize to different socio-cultural contexts. A related limitation is that we did not collect demographic information on a participant-level and, instead, had to rely on a community-level description of the sample. This is important to keep in mind when gauging the generalizability of our new measure.



**Fig. 5** TANGO demo website. We want to highlight that researchers are welcome to use and modify our task according to their needs. The number of training and test trials and the number of boxes can be

adjusted within the JavaScript code, while agents and targets can be exchanged within the HTML code

Finally, we utilized subtle gaze cues in order to increase difficulty and capture individual differences. However, in real-life settings, children could be more accustomed to a combination of head and eye orientation changes, and subtle gaze differences might be less common.

## Conclusions

We have presented a new experimental paradigm to study gaze understanding across the lifespan. The TANGO captures individual differences and shows highly satisfactory psychometric properties with respect to internal consistency and test-retest reliability. The browser-based testing infrastructure allows for standardized, portable data collection at scale, both remotely as well as in person. Associations with social-environmental factors and language skills illustrate the validity of the task. Ultimately, this work shows a promising way forward toward more precise measures of cognitive development. The data sets and the analysis code are freely available in the associated online repository (<https://github.com/ccp-eva/gazecues-methods>). A demo version of the task is available at the following website (see Fig. 5): <https://ccp-odc.eva.mpg.de/tango-demo/>. The code base and respective assets can be accessed in the following repository: <https://github.com/ccp-eva/tango-demo>. These resources allow interested researchers to use, extend and adapt the task.

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.3758/s13428-023-02159-5>.

**Author note** The authors made the following contributions. Julia Christin Prein: Conceptualization, Software, Formal Analysis, Writing—Original Draft Preparation, Writing - Review & Editing; Manuel Bohn: Conceptualization, Writing - Original Draft Preparation, Writing - Review & Editing; Steven Kalinke: Software, Writing - Review & Editing; Daniel B. M. Haun: Conceptualization, Writing - Review & Editing.

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**Open practices statement** The web application (<https://ccp-odc.eva.mpg.de/tango-demo/>) described here is open-source (<https://github.com/ccp-eva/tango-demo>). The data sets generated during and/or analyzed during the current study are available in the [gazecues-methods] repository (<https://github.com/ccp-eva/gazecues-methods>). All experiments were pre-registered (<https://osf.io/zjhsc/>).

## Declarations

**Conflicts of interest** The authors declare that they have no conflict of interest.

**Consent to participate** Informed consent was obtained from all individual participants included in the study or their legal guardians.

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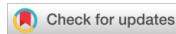
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## Study II



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RESEARCH ARTICLE

Developmental Science  WILEY

# Variation in gaze following across the life span: A process-level perspective

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#### Abstract

Following eye gaze is fundamental for many social-cognitive abilities, for example, when judging what another agent can or cannot know. While the emergence of gaze following has been thoroughly studied on a group level, we know little about (a) the developmental trajectory beyond infancy and (b) the sources of individual differences. In Study 1, we examined gaze following across the lifespan ( $N = 478$  3- to 19-year-olds from Leipzig, Germany; and  $N = 240$  20- to 80-year-old international, remotely tested adults). We found a steep performance improvement during preschool years, in which children became more precise in locating the attentional focus of an agent. Precision levels then stayed comparably stable throughout adulthood with a minor decline toward old age. In Study 2, we formalized the process of gaze following in a computational cognitive model that allowed us to conceptualize individual differences in a psychologically meaningful way ( $N = 60$  3- to 5-year-olds, 50 adults). According to our model, participants estimate pupil angles with varying levels of precision based on observing the pupil location within the agent's eyes. In Study 3, we empirically tested how gaze following relates to vector following in non-social settings and perspective-taking abilities ( $N = 102$  4- to 5-year-olds). We found that gaze following is associated with both of these abilities but less so with other Theory of Mind tasks. This work illustrates how the combination of reliable measurement instruments and formal theoretical models allows us to explore the in(ter)dependence of core social-cognitive processes in greater detail.

#### KEYWORDS

cognitive modeling, gaze following, individual differences, lifespan, social-cognitive development, Theory of Mind

#### Research Highlights

- Gaze following develops beyond infancy. The highest precision levels in localizing attentional foci are reached in young adulthood with a slight decrease towards old age.

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- We present a computational model that describes gaze following as a process of estimating pupil angles and the corresponding gaze vectors.
- The model explains individual differences and recovers signature patterns in the data. To estimate the relation between gaze- and vector following, we designed a non-social vector following task.
- We found substantial correlations between gaze following and vector following, as well as Level 2 perspective-taking. Other Theory of Mind tasks did not correlate.

## 1 | INTRODUCTION

Following the gaze of others is valuable for extracting information from the environment. It guides us to “informational hotspots” (Meltzoff et al., 2010, p. 1) and can be used to identify internal states such as intentions or emotions (Corkum & Moore, 1998; Pfeiffer et al., 2013). As one of the most fundamental social-cognitive abilities, gaze following is an integral part of almost every form of social interaction, including communication, collaboration, cultural and social learning (Bohn & Frank, 2019; Emery, 2000; Frith & Frith, 2012; Hessels, 2020; Moore, 2008; Rakoczy, 2022; Tomasello & Rakoczy, 2003), and has been extensively studied in infancy (for review, see Del Bianco et al., 2019). In the most commonly used paradigm (e.g., Astor et al., 2020; Byers-Heinlein et al., 2021; Gredebäck et al., 2010; Ishikawa et al., 2022), the experimenter looks directly at the infant before shifting their head and eyes to one of two objects. Infants’ looking times to the target or the proportion of choosing the target over the distractor are measured. Research in this tradition finds that infants as young as 3 to 4 months can follow the gaze of another agent (Astor et al., 2021; D’Entremont et al., 1997; D’Entremont, 2000; Del Bianco et al., 2019).

Previous research has shown a refinement of gaze following abilities in a child’s first and second year of life (e.g., Astor et al., 2021; Brooks & Meltzoff, 2002; Butterworth & Jarrett, 1991). At the end of their first year of life, infants can follow gaze to locations outside their current visual field and move themselves to gain proper perceptual access (Butterworth & Jarrett, 1991; Corkum & Moore, 1995; Deák et al., 2000; Moll & Tomasello, 2004). However, we do not know much about the developmental progression beyond these qualitative milestones. One possibility is that the ability to follow gaze does not improve beyond infancy. Yet, most, if not all, cognitive abilities continue to develop throughout childhood (e.g., Gathercole et al., 2004; Gredebäck et al., 2010). It seems likely that children fine-tune their gaze following as they get older—presumably while using them in social interactions. To capture the development in gaze following beyond infancy, Study 1 included participants from preschool to old age.

Until today, only a handful of gaze following studies differentiate between manipulating head and eye movement. Michel et al. (2021) found that gaze following in 4-month-olds was likely driven by other’s head- instead of eye movements. Corkum and Moore (1995), Lempers (1979), and Lempers et al. (1977) suggest that infants, at least until 19

months, struggle when eye and head direction diverge. From farther distance, body or face orientation can act as more salient cues to determine another’s area of attention. However, eye direction indicates a more precise location of focus (Emery, 2000; Stiefelhagen & Zhu, 2002; however, see Loomis et al., 2008 for peripheral vision), and allows us to anticipate likely future actions (Friesen & Rao, 2011; Zohary et al., 2022). The three studies included in this work, therefore, focused on subtle gaze cues and isolated eye movement alone.

Group-level analyses of gaze following abilities (e.g., the average age at which children as a group reach an above-chance performance) may mask individual differences between children. Measuring individual differences in basic aspects of social cognition is important to understand the underlying processes and to quantify the impact of environmental influences and other cognitive abilities (Birch et al., 2017; Del Bianco et al., 2019). Across the three studies, we measured gaze following continuously by using a task that is designed to capture individual-level variation (Prein et al., 2023): the TANGO (Task for Assessing Individual differences in Gaze understanding—Open) avoids floor and ceiling effects in children and adults and is thus particularly suited to examine how gaze following changes with age.

A promising approach to interpreting individual differences in cognitive abilities is computational cognitive modeling. Existing computational models have described gaze following via reinforcement learning (Ishikawa et al., 2020), as a consequence of goal interference and mapping self-experience onto other agents (Friesen & Rao, 2011) or an interplay of object distances/saliencies and head poses (Jasso & Triesch, 2006; Lau & Triesch, 2004; Recasens et al., 2015). As such, these models focus on the motivation behind gaze following or on situations in which the context (e.g., head orientation or surrounding objects) offers cues to the gaze direction. Our goal, however, was to formulate a theory that models how people estimate gaze direction based on the eyes alone (i.e., “literal” gaze following) when no target objects are present<sup>1</sup> and the other’s head is frontally oriented.

To our knowledge, there are three views that focus on the eyes alone that conceptualize gaze as (1) a beam, (2) a cone, or (3) a line (alternatively called a vector, ray, or line-of-sight). Guterstam et al. (2019) proposed the idea of gaze as a force-carrying beam. This theory, however, focuses on how people’s implicit assumptions about the physical properties of an object change when someone looks at it. The idea of gaze as a cone is mostly concerned with the question of

how people determine whether someone else looks at them (Gamer & Hecht, 2007; Horstmann & Linke, 2021). The conception most relevant to the present study sees eye gaze as a line: Yaniv and Shatz (1990) proposed that children extrapolate an imaginary trajectory between the agent and the object to identify the focus of attention (similar to “geometrical” gaze following; [Butterworth & Jarrett, 1991]). Anecdotal evidence was already reported by Walker and Gollin (1977), who observed two children pointing their fingers into the air, drawing a line between an agent and an object, and saying, “He sees that” (p. 354). Michelon and Zacks (2006) found that response time in Level 1 visual perspective-taking tasks depends on the distance between the agent and the object (i.e., the length of the line-of-sight). Some researchers additionally highlight iris eccentricity, that is, the ratio of the visible sclera on each side of the pupil (Anstis et al., 1969; Symons et al., 2004; Todorović, 2006). Todorović (2006) defined gaze direction as “the vector positioned along the visual axis, pointing from the fovea of the looker through the center of the pupil to the gazed-at spot” (p. 3550). Symons et al. (2004) furthermore reasoned that “the perceiver must use the asymmetrical configuration of the dark-white contrast of another individual’s eyes, and trace along two invisible sight-lines to their convergent point, that is, the third part of the triad (e.g., an object or a person)” (p. 452). Based on their finding that adults’ gaze direction sensitivity decreases when only one eye is shown, Symons et al. (2004) conclude that information from both eyes must be integrated.

While the previously mentioned conceptualizations focus on the direction of eye gaze, they (A) cannot explain how people differ in their abilities to precisely estimate gaze direction, and (B) are not clearly expressed as formal, mathematical models with explicit assumptions and testable predictions. In the words of (Gamer & Hecht, 2007): “Given the social relevance of determining gaze direction, the psychophysics of gaze is underdeveloped” (p. 705).

Here, we propose a cognitive model of gaze following, which builds upon the notion of eye gaze as line-of-sight tracing and extends this by explicitly modeling individual differences. Our gaze model assumes participants infer the locus of someone’s attention to be where two estimated gaze vectors meet. Each of these gaze vectors results from connecting the center of the agent’s eyeball and the center of the pupil. Because the center of the eyeball is not directly observable at that moment, vector estimation happens with a degree of uncertainty. Development of gaze following corresponds to a decrease in uncertainty. Individual differences correspond to systematic differences in uncertainty.

By focusing on individual differences, we can further address the relationship between gaze following and other cognitive abilities. A longstanding question has been whether gaze following is related to Theory of Mind (ToM) (e.g., Brooks & Meltzoff, 2015). Moll and Meltzoff (2011) have suggested that joint attention (including gaze following) might be seen as “Level 0 perspective-taking,” which provides the foundation for later-emerging, more complex perspective-taking abilities. On the other hand, an alignment of infants’ visual attention to another’s gaze does not necessarily indicate understanding the intentions of the agent (Aslin, 2007). Infants could simply align their orientation

without processing what exactly the other is seeing (Butterworth & Jarrett, 1991). In fact, one might question if such an alignment reflects an understanding of visual perspectives at all because the “target” or “object of representation” is not necessarily specified (Perner et al., 2003, p. 358). Consequently, Astor and Gredebäck (2022) have listed the relationship between gaze following and perspective-taking as one of their five big open questions in gaze following research. Therefore, in Study 3, we assessed how gaze following relates to ToM abilities, especially visual perspective-taking.

Taken together, the present study had three main goals: first, we studied the development of gaze following beyond infancy (Study 1). Instead of capturing the youngest age at which children follow the gaze, we examined how this ability changes with age. Our second goal was to provide a process-level theory of gaze following—and, most importantly, individual differences therein. We proposed a computational cognitive model, which formalized gaze following as a form of vector following, and tested whether our model explained empirical data (Study 2). Third, we examined which (social-)cognitive components comprise gaze following (Study 3). Based on our model, we predicted that gaze following should be related to non-social vector following. Additionally, we assessed the link between gaze following and ToM measures, with a particular focus on visual perspective-taking.

## 2 | STUDY 1: GAZE FOLLOWING ACROSS THE LIFESPAN

The study was pre-registered prior to data collection: <https://osf.io/snju6> (child sample) and <https://osf.io/6yjz3> (adult sample). The study obtained ethical clearance from the MPG Ethics Commission in Munich, Germany, falling under an umbrella ethics application (Appl. No. 2021\_45). Data was collected between May 2021 and April 2023.

### 2.1 | Participants

We collected data online from 3- to 80- year-olds (see [Supplementary information](#) for further details). The child sample consisted of 478 3- to 19-year-olds and was recruited via an internal database of families in Leipzig, Germany, who volunteered to participate in child development studies. Participants came from ethnically homogeneous, mixed socioeconomic backgrounds with mid to high parental education levels. They lived in an industrialized, urban Central-European context in a mid-size German city (approx. 600,000 inhabitants; median individual monthly net income approx. 1600€ as of 2021). Most were raised monolingually in a nuclear two-generational family setting. Information on demographics and socioeconomic status was not formally recorded on a participant level.

Adults were recruited via Prolific (Palan & Schitter, 2018). Prolific is an online participant recruitment tool from the University of Oxford with predominantly European and US-American subjects. Participants consisted of 240 English-speaking adults between 20 and 80 years of age who reported to have a normal or corrected-to-normal vision.



For completing the study, subjects were paid above the fixed minimum wage (~£10.00/h).

## 2.2 | Materials

We used the continuous version of the TANGO (Prein et al., 2023). The task was presented as a web application (demo <https://ccp-odc.eva.mpg.de/tango-demo/>; source code <https://github.com/ccp-eva/tango-demo>). The TANGO showed satisfactory internal consistency and retest reliability (Pearson's  $r$  from 0.7 to 0.8; Prein et al. [2023]) and no floor or ceiling effects for children and adults.

## 2.3 | Procedure

Children and teenagers received a personalized link to the study website. Caregivers were asked to provide technical support, while explicitly being reminded not to help in responding. Webcam videos were recorded whenever consented and technically feasible in order to monitor whether children and teenagers responded on their own. Adults completed the online study unsupervised.

Each trial presented an agent standing in a window, watching a balloon (i.e., target) falling to the ground (see Figure 4a; however, Study 1 presented animal agents). The target fell behind a hedge while the agent's gaze followed the target's trajectory. In test trials, a hedge covered the target's position. Participants were asked to touch or click where they estimated the target to be based on the agent's gaze. Four familiarization trials ensured participants understood the task and felt comfortable with the response format. Then, 15 test trials followed. Completing 19 trials took 5–10 min.

We measured imprecision, defined as the absolute difference between the target center and the x coordinate of the participant's click. The screen width was divided into ten bins. Within each bin, exact target coordinates were randomly generated. Each target bin, agent, and target color occurred equally often and did not appear in more than two consecutive trials.

## 2.4 | Analysis

We ran all analyses in R version 4.4.0 (2024-04-24) (R Core Team, 2022). Regression models were fit as Bayesian generalized linear mixed models (GLMMs) with default priors using the function `brm` from the package `brms` (Bürkner, 2017, 2018).

We fit GLMMs that make different assumptions about the developmental trajectory, modeling the relationship between age and performance as linear, quadratic, or cubic. In addition, we fit a Gaussian Process model (Bürkner, 2017), which assumes a smooth relationship but avoids enforcing a particular shape. Per individual, imprecision was aggregated across trials and modeled as a lognormal distribution.<sup>2</sup> The unit of imprecision was counted in target widths, that is, an imprecision of 1 meant clicking one balloon width to the left or right of the true

target center. We inspected the posterior distributions (mean and 95% credible interval [CrI]) for the age estimates and compared models via model weights and the difference in expected log pointwise predictive density (ELPD) estimated using leave-one-out cross-validation (LOO) (Vehtari et al., 2017).

To obtain a concise but principled characterization of the developmental trajectory, we additionally performed a Bayesian change point analysis, using the package RBeast (Zhao et al., 2019). We sought the most likely change points in our data, assuming a constant mean (i.e., a flat line, zero-degree polynomial) within each segment. To avoid "over-reactions" to outlying data points, we constrained the model to have minimally 10 data points between consecutive change points (= half of the data points collected per adult decade). We inspected the posterior probability of different numbers of change points and the locations of these change points (mean and 95% CrI).<sup>3</sup>

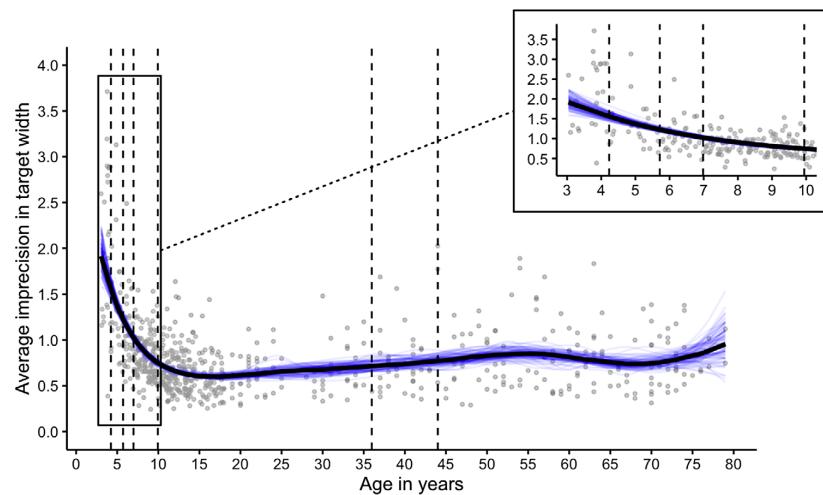
## 2.5 | Results

High levels of variation pointed to substantial individual differences in all age groups (overall imprecision mean = 0.81, SD = 0.82, range = [0–10.73]). We found strong evidence for a non-linear development in gaze following across the lifespan (see Figure 1). The Gaussian process model was clearly preferred over the polynomial models due to the highest predictive accuracy according to the LOO ELPD estimates: elpd\_diff between Gaussian process and cubic model = -33.75 (SE = 8.83); elpd\_diff between Gaussian process and quadratic model = -95.07 (SE = 15.19); elpd\_diff between Gaussian process and linear model = -127.17 (SE = 18.18); all in favor of the Gaussian process model. Moreover, the Gaussian Process model showed the greatest model weight (approximating 1). For the imprecision in gaze following, the standard deviation of the Gaussian process (SD = 1.52, 95% CrI [0.25; 5.19]) indicated nonlinearity.

The Bayesian change point analysis revealed 6 major shifts in gaze following during the lifespan (MAP estimate with 23.49% probability). The change points occurred at 4.23 years (95% CrI [4.13; 4.33], mean imprecision until change point = 2.15, SD = 0.85); 5.71 years (95% CrI [5.38; 5.90], mean = 1.36, SD = 0.53); 6.98 years (95% CrI [6.64; 8.04], mean = 1.06, SD = 0.40); 9.94 years (95% CrI [8.66; 12.55], mean = 0.82, SD = 0.23); 35.97 years (95% CrI [27.30; 39.69], mean = 0.65, SD = 0.23); and 44.01 years (95% CrI [40.37; 44.43], mean = 0.79, SD = 0.40). In short: we found a rapid initial improvement in gaze following in early childhood, followed by a long period of minor, very slow change with slightly increasing levels of imprecision toward old age.

## 2.6 | Discussion

We investigated the shape of change in gaze following across the lifespan and found a non-linear developmental trajectory, in which young children quickly enhanced their level of proficiency. Performance peaked around early adulthood, while there was a minor decay



**FIGURE 1** Developmental trajectory of gaze following across the lifespan. Gray dots show the mean level of imprecision (i.e., absolute distance between the target's center and the participant's click) for each subject averaged across trials. The unit of imprecision is counted in target width, that is, a participant with imprecision of 1 clicked on average one target width to the left or right of the true target center. Blue lines show 100 draws from the expectation of the posterior predictive distribution of the Gaussian Process model, with its mean predicted developmental trajectory as a solid black line. Vertical, black, dashed lines show the locations of the changes with the highest posterior probability according to our Bayesian change point analysis.

in later adulthood. These results support the idea that humans fine-tune their existing gaze following ability after the first emergence in infancy. Furthermore, we observed substantial individual differences in all age groups. While variation was highest in the 3- and 4-year-olds, it remained relatively stable across the lifespan.

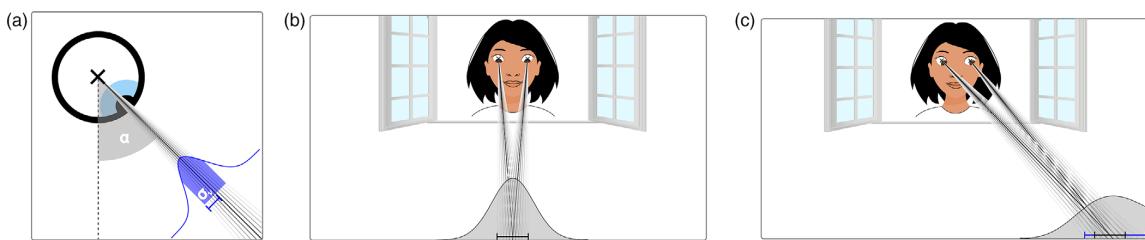
Previous studies found that already 4-month-olds demonstrate basic gaze following abilities (Del Bianco et al., 2019). Since we measured an active location choice on a touchscreen, we could not collect data from infants. In our sample, 3-year-olds were still rather imprecise in their gaze following ability (average imprecision was approx. two target widths). How can we explain this divergence? First, we used subtle eye movements as cues. Many existing studies let the agents move eye and head in parallel (Behne et al., 2005; Povinelli et al., 1997), establishing a confound with the more salient head movement. Relying exclusively on eye movements might be more difficult for children than presenting them with a combined eye and head orientation (Carpenter et al., 1998). Silverstein et al. (2021) used a similar manipulation of gaze cues without head rotation and found that 6- to 18-month-olds were around or just above chance for gaze following. The authors argue that infants might fixate on another's face most of the time, while eye movement alone might not be strong enough to guide their attention. Furthermore, our study required participants to (1) precisely follow an agent's gaze, (2) interpret this as a cue, and (3) use the cue to guide their own behavior. It is conceivable that 3-year-olds followed the agent's gaze but did not translate this into precise, active behavior. Moll and Kadipasaoglu (2013) argue that social forms of perspective-taking evolve prior to visual perspective-taking, which only emerges within the third year of life. Young children might simply not be interested in a differential, spatial representation of the surrounding objects. Taken

together, this might explain why our younger participants located the agent's gaze rather imprecisely.

Regarding our sample of elderly adults, we expect a sampling bias (Bethlehem, 2010; Gosling et al., 2004; Remillard et al., 2014). First, certainly, not all older people have a high-speed internet connection or are knowledgeable in its use. Second, the elderly adults participating in *Prolific* studies might show greater cognitive flexibility compared to their offline counterparts. Therefore, a representative sample may show a greater age decline in gaze following compared to our reported sample. In addition, older people might be more likely to suffer from visual impairments. Even though we filtered participants to only include normal- to correct-to-normal vision, we cannot guarantee that our participants showed no symptoms of reduced vision.

### 3 | STUDY 2: COMPUTATIONAL COGNITIVE MODEL

Our lifespan study showed that gaze following develops throughout childhood, and variation between individuals appears in all age groups. The TANGO has previously been shown to reliably capture inter-individual differences in gaze following (Prein et al., 2023). The variation between participants was thus likely genuine and not due to random noise. In Study 2, we aimed to understand the developmental change and individual differences on a process level. We present a theory of gaze following that explains how participants process the available gaze information and trace a line-of-sight to identify the agent's focus. We formalized this inference process in a computational cognitive model that replicates a schematic representation of how



**FIGURE 2** Gaze model. (a) Visualization of the gaze model (simplified, for one eye). Participants are assumed to observe the pupil location and estimate the center of the agent's eye. Connecting these two-point estimates as a line yields the unique vector that extends from the center of the agent's eyeball through the center of the pupil to the attentional focal point (line-of-sight). The angle between this vector and a line pointing vertically to the ground (black dashed line) is the pupil angle ( $\alpha$ ). Participants are assumed to sample (gray lines) from Normal distributions (blue line) centered around the true pupil angle. The variance of the Normal distribution ( $\sigma_v$ ) is expected to vary between participants. (b, c) Geometrical features of the gaze model. As the pupil angle varies, a fixed amount of uncertainty in the angle corresponds to a varying degree of uncertainty in the estimated target location. The distribution around the target location from which participants sample is wider when the agent gazes toward the side than when she gazes centrally. The blue line on the ground shows the added level of uncertainty in the estimated target position for the target location further outward (c).

participants make inferences in the task's context (i.e., a model of the task and not the data).

The study design and procedure obtained ethical clearance in the same way as Study 1. The study and the model were pre-registered prior to data collection: <https://osf.io/r3bhn>. Data were collected between May and August 2021.

### 3.1 | Computational model

Our model quantifies a participant's cognitive ability to follow gaze by inverting a probabilistic process that generates the participant's clicks from observing the eyes of the agent. It is formally defined as:

$$P(\theta|x_c, \alpha_l, \alpha_r) \propto P(x_c|\alpha_l, \alpha_r, \theta) P(\theta)$$

where  $\theta$  is an individual's cognitive ability to locate the focus of the agent's attention,  $x_c$  is the coordinate the participant clicked, and  $\alpha_l$  and  $\alpha_r$  are the pupil angles for the left and right eye, respectively. The pupil angle  $\alpha$  is defined as the angle between a line connecting the center of the eye to the pupil and a line extended vertically downward from the center of the eye (see Figure 2a)<sup>4</sup>. Please note that in our case, the center of the pupil is simultaneously the center of the iris (see Anstis (2018) for the influence of moving irises, pupils, and corneal reflexes).

Based on our verbal task instructions, we assumed that participants (1) expected the agent's looks to be directed at the target, and (2) to click on the coordinate they estimated the agent to look at. Consequently, we did not assume that participants' clicks were noisy in any way but that they clicked on the screen location where they genuinely thought the target was (and that the agent was looking at).

The true eye angles ( $\alpha_l$  and  $\alpha_r$ ) cannot be directly observed and have to be estimated based on the position of the pupils within the eyes, resulting in approximate values ( $\hat{\alpha}_l$  and  $\hat{\alpha}_r$ ). We presumed this estimation to be a noisy process. Thus, we conceptualized the development

of the cognitive ability to follow gaze as a reduction of noise in the estimates (i.e., an increased certainty about the pupil angles).

Any clicked value of  $x_c$  implied a "matched pair" of the estimated pupil angles  $\hat{\alpha}_l$  and  $\hat{\alpha}_r$ , with the property that lines extended along those two angles met at the precise location of the target. As a consequence, we can rewrite the likelihood function of the model above:

$$P(x_c|\alpha_l, \alpha_r, \theta) \propto P(\hat{\alpha}_l, \hat{\alpha}_r|\alpha_l, \alpha_r, \theta) P(x_c)$$

$P(x_c)$  is a prior over potential target locations, which we assumed to be skewed towards the screen center: We anticipated that participants have an *a priori* expectation that the target will land close to the middle, because the target was last visible in the screen center before disappearing behind the hedge and because the agent was located centrally on the screen. We estimated the strength of this center bias (i.e., the standard deviation of a Normal distribution around the screen center) based on the data:  $P(x_c) \sim \mathcal{N}(960, \sigma^p)$ .

The width of this distribution is defined by  $\sigma^p$ . For children, we assumed that the center bias changed with age and estimated  $\sigma^p$  via a linear regression as a function of the child's age ( $age_i$ ):  $\sigma^p = \beta_0^{sp} + age_i \cdot \beta_1^{sp}$ . Therefore, the participant-specific distribution for  $P(x_c)$  was constrained by the performance in the TANGO and the child's age. For the adults,  $\sigma^p$  was not age-specific.

The main inferential task for the participant lay in estimating the pupil angles, that is, sampling from the first term of the right-hand side equation above,  $P(\hat{\alpha}_l, \hat{\alpha}_r|\alpha_l, \alpha_r, \theta)$ . For this, we assumed that the pair of estimated pupil angles was sampled from a probability distribution which is the product of two Normal distributions of equal variance,  $\sigma_v$ , centered on the true pupil angles:

$$P(\hat{\alpha}_l, \hat{\alpha}_r|\alpha_l, \alpha_r, \theta) \propto \phi(\hat{\alpha}_l; \alpha_l, \sigma_v) \phi(\hat{\alpha}_r; \alpha_r, \sigma_v),$$

As  $\sigma_v$  determined the level of accuracy with which participants estimated the pupil angles, it is the component of the model that defines  $\theta$ . When  $\sigma_v$  is very small (i.e., the distribution around the pupil

angle is narrow), clicks far away from the target are unlikely, as these would require estimated pupil angles very different from the true pupil angles. When  $\sigma_v$  is very large (i.e., the distribution around the pupil angle is wide), almost any pupil angles may be sampled, corresponding to a roughly uniform distribution over click coordinates. We expected  $\sigma_v$  to vary between individuals. Consequently, individuals differed in the level of precision with which they can locate the target based on observing the agent's eyes.

The shape of the  $P(x_c|\alpha_l, \alpha_r, \theta)$  distribution leads to a testable group-level prediction. As the pupil location varies, a fixed amount of uncertainty around the pupil angle corresponds to a varying degree of uncertainty in the estimated target location (see Figure 2b,c). When the agent directs their gaze toward the very left or right side, the distribution around the target location from which participants sample is comparatively wider than when the agent gazes centrally to the ground. For illustrative purposes, imagine a similar phenomenon: pointing a torch light to a flat surface on the ground. When one points the light cone directly at the surface, the light beam is concentrated in a clearly defined, small, symmetric area. When one points the light cone further away from oneself (shining at an angle), the light from one half of the cone must travel further to reach the surface than the light from the other half, resulting in an asymmetric light pattern. As the angle increases, the light is spread over a wider area, and the surface is illuminated less evenly. Consequently, for the same  $\sigma_v$ , the further out a target coordinate lies, the wider and less symmetric the distribution. This increases both the variance and the bias in a participant's estimate of the agent's attentional focus, resulting in a decreased performance in the task. As  $\sigma_v$  decreases and the cone narrows, the extent to which performance varies at different angles decreases.

Our gaze model consequently predicted that TANGO trials vary in difficulty (see Figure 2b,c): participants should be more imprecise in locating the target the further out it lands, resulting in a U-shaped pattern<sup>5</sup>. If our data matched the pattern of this model prediction, this could act as evidence for the gaze model. Therefore, our gaze model provides a quantitative theory of gaze following. In the following, we tested these predictions in children and adults.

### 3.2 | Participants

The sample consisted of 60 children, including 20 3-year-olds (mean age = 3.47 years, SD = 0.34, range = 3.07–3.97, 11 girls), 20 4-year-olds (mean age = 4.61 years, SD = 0.26, range = 4.09–4.98, 10 girls), 20 5-year-olds (mean age = 5.66 years, SD = 0.24, range = 5.01–5.96, 12 girls). Children were recruited via an internal database, where parent previously consented to child development studies, and data was collected in kindergartens in Leipzig, Germany.

In addition, we included 50 adults from Study 1 (mean age = 31.92 years, SD = 12.15, range = 18–63, 36 female). Since developmental change was minimal in our adult sample (see Study 1) and the cognitive models were computationally heavy, we decided to only include the first 50 adults who had completed the study.

### 3.3 | Procedure

We applied the same procedure as in Study 1. Children were tested in a quiet room in their kindergarten, while an experimenter guided the child through the study on a tablet. Adults participated online.

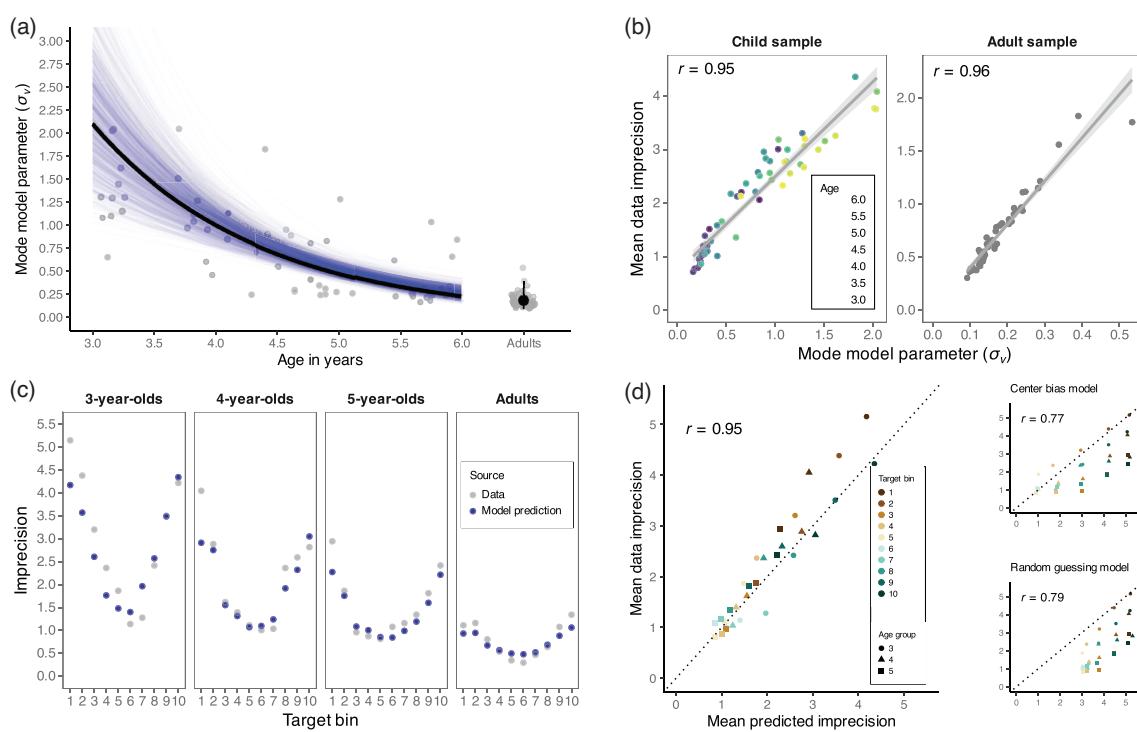
### 3.4 | Analysis

We quantified how well our gaze model explained the gaze following process in two ways. First, we aggregated the model predictions and data for each target bin and age group (3-, 4-, 5-years-olds, adults), and computed correlation to quantify how well the model was able to recover the data. Second, we compared the predictions of our gaze model to two simple alternative models that assume participants do not rely on the agent's gaze at all: a random guessing model and a center bias model. The random guessing model assumed participants randomly clicked on the screen and was implemented as sampling from a uniform distribution over all possible coordinates,  $U(0, 1920)$ . The center bias model assumed participants always clicked near the screen center and was implemented as sampling from a Normal distribution with the screen center as the mean, and one balloon width as the variance,  $N(960, 160)$ . Note that the center bias model also predicted imprecision should be higher for targets further out on the screen. However, compared to the gaze model, it predicted a steep effect towards the sides, resulting in a V-shaped pattern (imprecision as the distance between the target location and the screen center). All cognitive models were implemented in WebPPL (Goodman & Stuhlmüller, 2014).<sup>6</sup>

We compared models via the marginal likelihood of the data under each model. The pairwise ratio of marginal likelihoods for two models is also known as the Bayes Factor, which quantifies the quality of a model's predictions by averaging over the possible values of the model's parameters weighted by the prior probabilities of those parameter values. It can be used to estimate how much more likely the data under one model are compared to the other. Bayes Factors implicitly consider model complexity: models with more parameters often have broader prior distributions over parameters, which might weaken potential gains in predictive accuracy.

### 3.5 | Results

We found very clear support for our gaze model, both in children as well as adults. A strong correlation between the data mean and the gaze model estimate ( $\sigma_v$ ) showed that the data mean is suitable to quantify individual differences: child sample  $r(60) = 0.95$ ,  $p < 0.001$ , 95%CI [0.92, 0.97]; adult sample  $r(50) = 0.96$ ,  $p < 0.001$ , 95%CI [0.93, 0.98]. The gaze model predicted a U-shaped pattern which we also observed in our data (see Figure 3c). The model comparison strongly favored our gaze model over the center bias model (child sample  $\log BF_{10} = 1015.33$ ; adult sample  $\log BF_{10} = 2575.75$ )



**FIGURE 3** Gaze model results. (a) Developmental trajectory of the estimated model parameter. Gray dots show individual level parameter values. The black line shows the maximum a posteriori (MAP) estimate; blue lines show 1000 draws from it. The large black point with 95% HDI shows the mean of the model parameter for the adult sample. We added minimal horizontal and vertical noise to the adult individual level parameter values to avoid overplotting. (b) Correlation between estimated mode of the model parameter and data mean per individual, faceted by age group. In the child sample, color denotes age in years. Gray regression lines with 95% CI show smooth conditional means based on linear models, with Pearson's correlation coefficient  $r$ . (c) Pattern recovery. Imprecision in target width for each target bin by age group. Model predictions in blue; data in gray. (d) Correlation between the observed data and the predictions of the three models by target position and age group (across individuals; only for the child sample).

and the random guessing model (child sample  $\log BF_{10} = 388.98$ ; adult sample  $\log BF_{10} = 919.03$ ). For the child sample, we went one step further into the analysis. When correlating the observed data across all target positions and age groups with the predictions of the three models, we found a high similarity for the gaze model:  $r(30) = 0.95$ ,  $p < 0.001$ , 95%CI [0.90, 0.98], while the correlations with the alternative models were smaller (center bias model:  $r(30) = 0.77$ ,  $p < 0.001$ , 95%CI [0.57, 0.89]; random guessing model:  $r(30) = 0.79$ ,  $p < 0.001$ , 95%CI [0.59, 0.89]). The gaze model's prior over potential target locations assumed that participants' clicks would be skewed towards the screen center. For children, we estimated the width of the prior's distribution based on the participants' age. Interestingly, we found that the differential age effects on the center bias prior were minor (intercept = 300.14, 95% highest-density interval (HDI) [277.19; 321.28]; slope = 1.18, 95%HDI [0.00; 18.78]). The slope of the prior indicated that older children were only marginally less drawn towards the screen center compared to the younger children.

### 3.6 | Discussion

We presented a formal cognitive model of gaze following to describe how gaze following develops with age and varies between individuals. We modeled gaze following as a process in which participants estimate pupil angles based on the pupil location within the eye. By following the resulting gaze vector, they consequently arrive at the attentional focus of the agent. Individual differences can be explained as varying levels of imprecision in the pupil angle estimation. We assume the basic process of gaze following to be the same across the lifespan, though individuals become increasingly precise with age. While we did not include an infancy sample, we believe the process of gaze following should operate similarly—if not other cues such as the object saliences or head directions are followed instead. By conducting model comparisons, we ruled out simpler explanations of the data.

In addition, we observed differences in performance depending on gaze location: participant data showed that precision levels dropped as the agent's gaze moved further away from the center.

Our gaze model predictions recovered this “signature pattern” in the data. Future research could use this signature in the data as evidence of whether diverse communities employ the same inferential mechanism to solve the task, speaking for a shared cognitive architecture.

Interestingly, the U-shaped pattern in the TANGO can be conceptually compared to the result patterns of Michelon and Zacks (2006): in their Level 1 perspective-taking task, an increased distance between the agent and the target decreased performance in adults (i.e., reaction times). Targets closer to the midline were more easily traced than ones further away from the agent. The authors concluded that visual acuity is generally higher for locations on the vertical than the diagonal axis (“oblique effect”; [Appelle, 1972; Heeley et al., 1997; Mikellidou et al., 2015]). Similarly, Symons et al. (2004) have found that adults’ acuity for gaze direction depends on the target location. Not only is the increased imprecision for TANGO trials in which the target lands further out consistent with this finding, but our gaze model poses a viable explanation for this effect.

A limitation of our model is that we cannot disentangle how much of the participants’ uncertainty comes from a noisy estimate of the agent’s attentional focus and how much is due to imprecise clicking (e.g., experiencing motor issues, adding random noise to the click). However, we believe imprecise clicking to be of minor concern, since the children in our sample seemed determined in where they clicked and to not have issues with aiming or motor control (see precision in training trials in *Supplementary information*).

A critical feature of our model is that it assumes gaze following to rely on vector following: subjects are modeled to calculate pupil angles which serve as gaze vectors to point to the attentional focus point of an agent. Even though this vector following component is a geometrical calculation, one must first interpret the agent’s eyes as a relevant social stimulus. Therefore, our model describes gaze following as a particular form of vector following in a social context.

Previous models in the social- and non-social cognitive domain exist that also make use of the concept of vector estimation (see Madl et al. (2015) for a review of computational models for spatial memory). For example, Brom et al. (2012) defined egocentric self-to-object vectors and allocentric object-to-object vectors where corresponding uncertainties due to memory and motor errors were modeled by vector weights and Gaussian noise. The counterfactual simulation model (Gerstenberg et al., 2014, 2021; Gerstenberg & Lagnado, 2012; Gerstenberg & Stephan, 2021) used vector calculations to model causal reasoning; for example, in estimating billiard ball trajectories and their collisions. Gaussian noise was added to the ball’s movement vector to represent people’s prior expectations, uncertainties, and expertise (the stronger the expectations, the less noise is added to the vector). Therefore, the way these models capture individual differences resembles the approach taken in the here-proposed gaze model.

The idea of gaze as vector following has recently been introduced to the study of pointing gestures (O’Madagain et al. (2019), see Li et al. (2023) for computational modeling). According to this hypothesis, when humans use pointing gestures, the index finger does not consti-

tute an “arrow” pointing at the target, but is used to touch the object within one’s visual field. Consequently, the touch line is a vector that connects the eye and the pointed fingertip, and marks the object that the person’s fingertip seems closest to touching from her perspective (O’Madagain et al., 2019). This supports the idea that vector estimation is relevant for social-cognitive abilities.

## 4 | STUDY 3: COMPONENTS OF GAZE FOLLOWING

Study 3 examined the components of gaze following and whether it can be fully reduced to physical vector following. The positive link between TANGO and social-environmental factors like age of childcare entry (Prein et al., 2023) underline how social interaction is integral to gaze following. Nevertheless, it is unclear how gaze following relates to other forms of perspective-taking (Astor & Gredebäck, 2022). Therefore, we investigated associations between gaze following and other measures of social-cognitive abilities.

First, we experimentally isolated the vector following component of the TANGO. We designed a new non-social vector following task that shared all crucial design features of the TANGO. Second, we assessed children’s social-cognitive abilities by administering a ToM task battery, comprising four tasks from the ToM scale by Wellman and Liu (Wellman & Liu, 2004) and two additional perspective-taking tasks (Flavell, Flavell, et al., 1981; Flavell, Everett, et al., 1981). We reasoned that the TANGO shares task demands with the non-social vector following task while it shares its social context with the ToM tasks. We could, therefore, imagine both an absence or presence of relationship between gaze following and ToM. As stated in our pre-registration, we further assessed whether the two perspective-taking tasks related to gaze following. Our reasoning was that similar underlying mechanisms might be needed to solve these tasks since they require participants to take into account another person’s point of view.

The study design and procedure obtained ethical clearance in the same way as Study 1. The study was pre-registered prior to data collection: (<https://osf.io/xsqkt>). Data collection took place in Leipzig, Germany, between February and March 2023.

### 4.1 | Participants

The sample consisted of 102 children (mean age = 4.54 years, SD = 0.31, range = 3.99–5.03, 54 girls). Information on individual socio-economic status was not formally recorded.

### 4.2 | Procedure

Children were tested in a quiet room in their kindergarten. An experimenter guided the child through the study. For maximum control of extraneous participant variables, we employed a within-subjects study



design. Participants performed the tasks in this order: (1) non-social vector following task, (2) ToM task battery, (3) TANGO. We decided on a fixed order to compare participants' performance straight-forwardly with each other. To increase engagement and decrease fatigue or fuzziness, we switched between tablet tasks and tasks with personal interaction. We presented the non-social vector following task before the TANGO so that participants would not be biased to interpret the stimuli as "agent-like."

#### 4.2.1 | Non-social vector following

Modeling the structure of the TANGO, we designed a non-social vector following task. This task was presented on a tablet and used the concept of magnetism. On the upper part of the screen, there was a tube with a circular window, containing a gearwheel. On the floor, there was a magnet. The magnet got switched on (with a cartoon-like sound), whereupon the gearwheel moved towards the magnet. The gearwheel moved so that its center aligned with the magnet center while staying inside the circular window. Participants were then asked to locate the magnet. Access to the magnet's true location was manipulated by a wooden wall: participants either had full, partial, or no visual access to the true magnet location. Compared to the TANGO, the circular window acted functionally similar to the agent's eyeball, while the gearwheel acted similar to the pupil. Participants were expected to estimate a vector from the center of the circular window to the gearwheel and extend this as a line toward the ground to locate the magnet. We deliberately decided against displaying an arrow: we aimed to keep the mechanistic functions of the TANGO and magnet stimuli as similar as possible. In both cases, the starting point of the vector needs to be estimated by the participant. With an arrow, we would have drastically reduced the level of uncertainty, since the arrow already displays all information (arrow tip as the "gaze" direction). Furthermore, we wanted to avoid referential or iconic stimuli.

Children received 19 trials with one full visual access trial, two partial visual access trials, and 16 test trials. The first trial of each type comprised a voice-over description of the presented events. We conducted our analysis with 15 test trials (excluding the voice-over trial). The outcome variable was imprecision, defined as the absolute distance between the magnet's x coordinate and the x coordinate of the participant's click. Magnet coordinates were randomized: The full width of the screen was divided into ten bins; each bin occurred equally often, while the same bin could occur in two consecutive trials; and exact coordinates within each bin were randomly generated.

#### 4.2.2 | ToM task battery

We administered four tasks from the Wellman and Liu (2004) ToM scale (see [Supplementary information](#) for further detail). We excluded three tasks: the Diverse Desires task to avoid ceiling effects; and

both tasks involving emotions (Belief Emotion and Real-Apparent Emotion), as we aimed at assessing the "cold, cognitive" (vs. "emotional") aspects of social cognition. We added two perspective-taking level-2 tasks ((Flavell, Flavell, et al., 1981; Flavell, Everett, et al., 1981); where children were asked whether a turtle appeared to be on its back or feet/a worm lay on a red or blue blanket from the experimenter's point of view) with the aim of increasing the variability we can capture between individuals, and since we hypothesized that perspective-taking would rely on similar mechanisms than gaze following, both relying on another's person egocentric frame of reference.

#### 4.2.3 | Gaze following

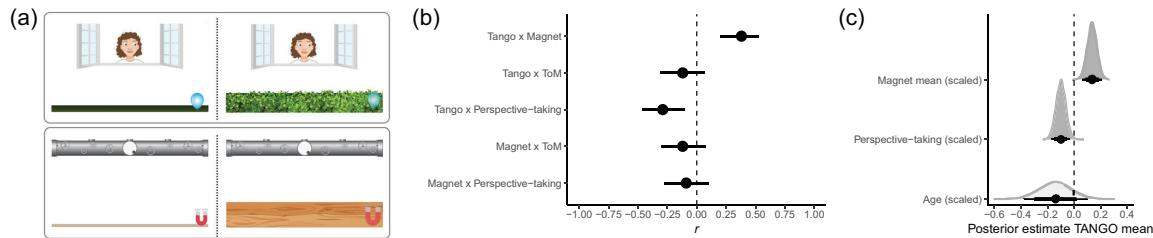
As in Study 1 and 2, we presented children with the TANGO (Prein et al., 2023). To accentuate the social aspect of the TANGO, we exchanged the animal agents (used in the previous two studies) with human faces, which were modeled after the local population in appearance (already created for another project on cross-cultural similarities in gaze following [<https://osf.io/tdsvc>]). This further highlighted the contrast (i.e., social vs. non-social context) to the non-social vector following task.<sup>7</sup>

### 4.3 | Analysis

By design, the TANGO and the non-social vector following task involved vector following. Based on our computational model, we expected children's performance in both tasks to correlate with each other. For each task, we calculated the mean level of imprecision for each subject and correlated them using Pearson's correlation coefficient.

For the ToM battery, we aggregated the score of all solved tasks. Please note that the ToM score acted as an umbrella term and included the two perspective-taking tasks. Regarding the relationship between the two vector following tasks and the ToM measures, we could imagine two possible scenarios: (A) If gaze following recruited a social-cognitive ability beyond geometric vector following, we expected that ToM measures would correlate more strongly with the gaze following task than with the non-social vector following task. (B) If gaze following relied purely on task-specific geometric processes, then the correlation between gaze following and ToM measures would be comparable to the correlation between non-social vector following and the ToM measures. For the association between the aggregate ToM scores and the gaze following/non-social vector following tasks, we used Spearman's rank correlation coefficients.

We compared the correlation between gaze following and ToM measures and the correlation between non-social vector following and ToM measures by using the Williams' test from the function cocor.dep.groups.overlap (designed for two dependent overlapping correlations) from the package cocor (Diedenhofen & Musch, 2015).



**FIGURE 4** Components of gaze following. (a) Study procedures. Top: TANGO (i.e., gaze following; social vector following). Bottom: Magnet (i.e., non-social vector following). The left-hand side shows screenshots of the familiarization phase; right-hand side shows screenshots of the test phase. For illustrative purposes, translucent targets are shown in the test phase. Participants cannot see them. (b) Correlations between gaze following, non-social vector following, ToM, and perspective-taking. Dots show the correlation coefficients, error bars represent 95% CIs. Please note that the ToM score acts as an umbrella term and also includes two perspective-taking tasks. (c) Influence of age, perspective-taking and non-social vector following on gaze following. The graph shows the posterior distributions for the respective predictor. Black dots represent means, thicker black lines 80% CrI, and thinner black lines 95% CrI.

To estimate which components best explain the gaze following score, we conducted a model comparison with GLMMs predicting the mean imprecision in gaze following by age, imprecision in non-social vector following, the ToM aggregate score, or the aggregate of the two perspective-taking tasks (subset of ToM battery; example of model notation in R: `tango_mean ~ age_centered + magnet_scaled + perspective_scaled`). The outcome variable was modeled by a lognormal distribution. We wanted to assess whether the ToM aggregate score or the singled-out perspective-taking score added additional explanatory value when predicting the gaze following score. We hypothesized that perspective-taking seemed most closely theoretically related to gaze following as in both cases the participant was asked to judge another person's point of view.

#### 4.4 | Results

Children performed similarly well in the social and non-social vector following tasks (gaze following mean = 1.92, SD = 0.77, range = [0.57–4.49]; vector following mean = 1.90, SD = 1.01, range = [0.57–5.83]). The mean aggregate ToM score was 3.46 (SD = 1.53, range = [0–6]), while the mean aggregate perspective-taking score was 1.38 (SD = 0.81, range = [0–2]).

Gaze following substantially correlated with the non-social vector following task,  $r(102) = 0.38, p < 0.001, 95\% \text{CI} [0.20, 0.53]$  (see Figure 4b). While the tasks highly overlap in task demands, their measures shared some, but not all of their variance.

ToM abilities did not correlate with gaze following ( $\rho(102) = -0.12, p = 0.22, 95\% \text{CI} [-0.31, 0.07]$ ) or non-social vector following ( $\rho(102) = -0.12, p = 0.25, 95\% \text{CI} [-0.30, 0.08]$ ), and the correlations did not differ from each other, Williams' test  $t(99) = 0, p = 1$ .

Interestingly, gaze following and perspective-taking correlated with each other,  $\rho(102) = -0.29, p < 0.01, 95\% \text{CI} [-0.46, -0.10]$ . Please note that the TANGO quantifies imprecision in gaze following. Therefore, a negative correlation suggests that imprecision in gaze following corresponds to less perspective-taking. Non-social vector following and

perspective-taking did not correlate,  $\rho(102) = -0.09, p = 0.36, 95\% \text{CI} [-0.28, 0.10]$ . However, according to the Williams' test, the two correlations did not differ significantly from each other,  $t(99) = -1.86, p = 0.06$ .

Our model comparison revealed that gaze following was best predicted by a model including non-social vector following ( $\beta = 0.14, 95\% \text{CrI} [0.06; 0.21]$ ) and perspective-taking ( $\beta = -0.10, 95\% \text{CrI} [-0.17, -0.03]$ ), even when controlling for age ( $\beta = -0.14, 95\% \text{CrI} [-0.38, 0.10]$ ) (see Figure 4c and *Supplementary information* for the model comparison).

#### 4.5 | Discussion

Our gaze model assumed vector calculations on a process level. By isolating non-social vector following experimentally, we could show that gaze following does indeed, to a certain degree, rely on this component. However, non-social vector following alone did not suffice to explain variation in gaze following. Additionally, perspective-taking proved to be a relevant social-cognitive ability when predicting the performance in the TANGO. The overall ToM aggregate score did not add explanatory power.

The TANGO and the two perspective-taking tasks can be seen as instances of visuospatial perspective-taking. Often, researchers distinguish between Level 1 and Level 2 perspective-taking tasks. Level 1 perspective-taking is concerned with the visibility of objects from a particular viewpoint (Surtees et al., 2013), and can usually be solved independently from another's agent frame of reference and without mental rotation [not matching the "mentalizing criterion"; Quesque and Rossetti (2020)]. In contrast, Level 2 perspective-taking tasks ask participants to judge how (visually or conceptually) the world looks for another person. Solving these tasks presumably relies on a simulation of mentally transforming one's own body schema into the space of another agent (Erle & Topolinski, 2017). Participants must understand that different viewpoints lead to different perspectives (Flavell, Everett, et al., 1981): two agents can see the same object "in different, incompatible, fine-grained ways" (Rakoczy, 2022). In short,



Level 1 perspective-taking addresses *what* an agent can see, while Level 2 perspective-taking addresses *how or where* they see it (Moll & Tomasello, 2006). The TANGO falls into the first category—however, in contrast to existing research, on a continuous scale—while the perspective-taking tasks presented within the ToM scale fall into the second category.

In the TANGO, participants locate the target by assuming that another agent perceives and looks at it. The here-applied Level 2 perspective-taking tasks add another layer by asking how one's perspective differs from another's and how exactly the other person sees an object. Michelon and Zacks (2006) assessed the different processes that participants used to master Level 1 and Level 2 perspective-taking tasks and concluded that participants rely on line-of-sight tracing in the former and perspective transformation in the latter case. Line-of-sight tracing consists of locating the avatar and the target, and drawing a line between them. Note how our gaze model in Study 2 shares the underlying idea of connecting points in space via a line. Level 2 perspective-taking requires an additional step in which participants "perform a perspective transformation so that one's imagined position matches the position of the avatar" (Michelon & Zacks, 2006). Therefore, the processes to solve Level 1 perspective-taking tasks might be computationally lighter since there is no need to adapt a new reference frame and there is no potential conflict between one's own and the other person's reference frame. Still, the assumed processes overlap, which could explain the correlation between the TANGO and the administered perspective-taking tasks.

Surtees et al. (2013) further differentiated between visual and spatial perspective-taking. While the former helps to judge if and how an agent sees an object, the latter involves judging the relative spatial locations of an agent and the object. Spatial perspective-taking does not necessitate mental states since computing a line of sight does not demand the presence of another agent (Michelon & Zacks, 2006) and can, therefore, be applied to non-agentive objects with a front (Surtees et al., 2013). This could explain how our participants solved the non-social vector following task.

Interestingly, we found weaker correlations between gaze following and the other ToM tasks. Similarly, in a longitudinal study, Brooks and Meltzoff (2015) found no direct association between gaze following at 10.5 months and explicit ToM at 4.5 years. While the ToM tasks and the TANGO shared the social context, the cognitive processes needed to solve each task might vary. As Rakoczy (2022) reflected, perception-goal psychology (which includes gaze following) comprises understanding that others see different objects or pursue different goals. However, this ability does not necessarily entail understanding more complex meta-representational aspects; for example, understanding that mental states can be false or involve aspectual information.

In previous work, we established that the TANGO is suited to capture meaningful variability across individuals (Prein et al., 2023), which is a crucial task feature when we are interested in revealing the relationship between different cognitive abilities. Importantly, the tasks we used to measure ToM abilities were not designed to capture individual differences: the aggregate score of few dichotomous items is of

limited use when it comes to quantifying genuine differences between individuals. However, since these tasks are the gold standard in the social-cognitive literature (Bialecka-Pikul et al., 2021; Byom & Mutlu, 2013; Poulin-Dubois et al., 2023; Rakoczy, 2022; Wellman, 2018), and measures with satisfying psychometric properties are, to the best of our knowledge, still scarce (e.g., Beaudoin et al., 2020; Mayes et al., 1996), we nonetheless relied on them in this study. Thus, lower correlations between ToM abilities and gaze following may reflect poor measurement characteristics on the side of ToM tasks rather than a genuine absence of association. We would like to point out that we already stated this concern in our pre-registration (<https://osf.io/xsqkt>).

If the reliability of the tasks at hand is known, one can estimate the "true" correlation between the latent constructs by applying an attenuation formula or structural equation models (Metsämuuronen, 2022; Trafimow, 2016). Adjusting for the measurement error would increase the so-called true correlation. While we can estimate the split-half reliability for the TANGO (Prein et al., 2023) and the non-social vector following task, we do not have reliability estimates of the ToM measures and cannot apply said approaches. This, in turn, underlines the importance of reporting the psychometric properties of a task. The development of new measures to capture individual differences in social-cognitive abilities seems essential to move this research further.

## 5 | GENERAL DISCUSSION

In three studies, we shed light on the cognitive process underlying gaze following and its developmental trajectory across the lifespan. Study 1 focused on how gaze following changes with age. We found a steep performance improvement in the preschool years in which children became more precise in locating the attentional focus of an agent. During teenage years and early adulthood, participants reached their peak performance. Precision levels then stayed comparably stable, with a minor decay toward older adulthood. Beyond these aggregated developmental patterns, we found that individual differences exist throughout the lifespan. In Study 2, we proposed a computational cognitive model that described gaze following at a process level. We modeled gaze following as a process in which participants use the pupil location within the eyes to estimate pupil angles. To locate the attentional focus of an agent (and find a target), they extend the resulting gaze vector towards the ground. Individuals vary in their levels of uncertainty around these pupil angles. Our gaze model outperformed two alternative models, which assumed participants solved the task via a center bias or random guessing. Knowing the TANGO to be a reliable individual differences measure, we investigated potential components of gaze following in Study 3. A fundamental assumption of our computational model was that gaze following relies on a vector following process. We experimentally isolated this component by designing a non-social vector following task. Furthermore, we assessed the relationship between gaze following and traditional ToM tasks. We found that gaze following does, indeed, share a substantial part of its variance with the non-social counterpart of vector following. Additionally,

perspective-taking correlated with gaze following, whereas the other ToM measures (focusing on diverse desires, knowledge access, and false beliefs) did not.

The developmental trajectory seen in Study 1 shows how abilities that emerge in infancy can continue to develop throughout childhood. While previous research established that 4-month-olds can follow gaze toward one out of two objects, this is not the end point of development. By studying gaze following on a continuum, we assessed not just *whether*, but *how precisely* children locate others' attentional focus. In previous work, we have shown that these individual differences are meaningful (e.g., connected to theoretically related constructs, and showing high split half and retest reliability; [Prein et al., 2023]). Capturing individual variation is crucial when we study development and the improvement in social-cognitive abilities.

Preschool children increased their precision level to locate an agent's attentional focus, which then stayed comparably stable across adulthood. Older adults decreased slightly in their precision levels. This developmental trajectory of a first emergence with a rapid improvement, followed by a plateau and slight decline toward older age, might be representative of many cognitive processes.

In Study 2, we proposed a theoretical framework to interpret the development and individual differences in gaze following. Our computational cognitive model assumes that participants estimate a pupil angle (i.e., the angle between a line extending vertically downwards from the pupil center and a line connecting the pupil and eye center; line-of-sight; see Figure 2a). The model parameter estimates a participant's latent ability to follow gaze and can explain why individuals differ in their precision to locate an agent's attentional focus. The model proposes that development in gaze following equals a reduction in noise when estimating the agent's pupil angles. We found strong evidence for the proposed gaze model when comparing it against two alternative models and correlating its predictions with the observed data (see Figure 3d), both for children and adults. Notably, the model recovers signature patterns in the data (see Figure 3c).

In Study 3, we tested the relation between gaze following and non-social vector following. As implied by our gaze model, we found that gaze following relates to the ability to estimate vectors in space. Already Butterworth and Jarrett (1991) have argued that, as the scene of actions, space is the commonality between different minds. The spatial vector following ability might be helpful in several social-cognitive tasks, for example, action prediction (Friesen & Rao, 2011), and intention understanding. Predicting which object another agent likely wants to grasp or calculating their movement pathway could rely on similar vector following abilities.

Gaze as displayed in the TANGO versus as in real-life social interactions differs with regard to which information is available. In the TANGO, the agent's eyes are big and round, with uniform colors, white sclera, fully visible iris and pupils, and continuous eye movement. The start position of the pupil is the center of the agent's eyeball—which, later on, needs to be estimated. Eye gaze in natural social interactions often provides less information and is more ambiguous. Even though the TANGO and our gaze model are designed within a 2D world, we believe the mechanisms can be extrapolated into the 3D

world. The processes of understanding gaze in daily life likely rely on the same principles as proposed in this paper. In Study 3, we presented the first evidence that this might be the case. We administered Level 2 perspective-taking tasks in which participants needed to adapt another person's frame of reference in a real-world social interaction. The correlation between this task and the TANGO speaks toward a unified mechanism behind these two visual perspective-taking tasks, regardless of the testing setup or stimulus features. Clearly, our real-life environment is visually more cluttered and diverse than the one presented in our tablet task. Here, however, additional informational sources are available to infer where others are looking; for example, body or head orientation or common ground (Bohn & Köyメン, 2018; Moll & Kadipasaoglu, 2013; Osborne-Crowley, 2020). From a modeling perspective, a shared interaction history or diverse desires might be represented as non-uniform prior distributions over locations in the visual scenery. This way, our gaze model could be expanded to include more complex processes like mental state reasoning.

Theories of gaze following differ in whether they illustrate why children pay attention to gaze in the first place versus how they identify the exact location of gaze. While we described the process behind children's increasing precision in gaze following, we still need to further explore the driving forces behind this development. Existing theories broadly vary in how much importance they place on (A) experience and social environment, and (B) social awareness versus domain-general learning mechanisms (see categorization by Astor and Gredebäck [2022]). For example, it has been hypothesized that infants might be equipped with an innate gaze module and special neural mechanisms to detect eyes (Baron-Cohen, 1995; Batki et al., 2000); that children identify contingencies in social interactions and, in these, get reinforced to follow gaze (Corkum & Moore, 1998; Silverstein et al., 2021; Triesch et al., 2006); or that children are intrinsically socially motivated and simulate their own experiences to understand others (Astor et al., 2020; Friesen & Rao, 2011; Ishikawa et al., 2020; Meltzoff, 2007; Tomasello, 1999). As seen in Prein et al. (2023), precision in gaze following is linked to receptive vocabulary and opportunities for social interaction (e.g., number of siblings and age when entering childcare). Which exact kind of interactions are most helpful to improve precision in gaze following remains unknown.

## 6 | LIMITATIONS

In this paper, we have focused on studying variation across ages and individuals. However, our findings rely on participants from Western, Educated, Industrialized, Rich, and Democratic (WEIRD) backgrounds (Henrich et al., 2010). Cultural variation has been found in many foundational aspects of cognition and socialization: for example, in parent-child interaction and communication (Nielsen et al., 2017). First evidence suggests that cultural variation in face-to-face interactions does not influence infants' gaze shifts (Hernik & Broesch, 2019). While we cannot generalize our here-reported developmental trajectory to different socio-environmental settings, we predict that our presented process-model of gaze following holds true across communities.



Analyzing cross-cultural variation and checking for predicted "signature patterns" in the data will inform our modeling work and theory building in further detail (Amir & McAuliffe, 2020).

In Study 1, we recruited older participants online which might have selected a particular subgroup of this age range. Seventy-year-olds who have working Wi-Fi connections, know how to use a computer, and are registered on Prolific might not be representative of their age group. We can imagine that results from a more diverse, in-person data collection might show different developmental trajectories toward old age.

Our computational model of gaze following estimates one person-specific parameter for how accurately participants locate another person's attentional focus. The model assumes no motor imprecision in this estimation. However, younger children could have located the agent's focus at one particular point but clicked somewhere slightly off for motor control reasons. This would blur the model's estimation of the inferential component. However, in the first training trial, in which children were simply asked to touch the balloon, we found nearly perfect precision levels (cf. Prein et al., 2023). Motor issues and inaccurate aiming, resulting in falsely wide estimations in the model's inferential component, seem unlikely.

In Study 3, we matched the non-social vector following task as closely as possible to the TANGO. However, the starting positions differ: the magnet never appeared in the center of the screen. The starting point of the balloon might be especially important when interpreting the U-shaped pattern in Study 2. Furthermore, in the TANGO, two eyes are presented and information of the two (matching) cues needs to be integrated to infer the target's location. In the non-social vector following task, only one circular window with a gearwheel inside is presented as a directional cue, and there is no need to integrate two different information sources. In addition, we want to mention that the gaze presented in the TANGO might be more prominent compared to real-life social interactions (e.g., perfectly round and visible sclera; see discussion above). Future research should investigate how factors like self-propelled movement, spatial layout, and number of information sources influence the mechanisms of gaze following.

## 7 | CONCLUSION

In three studies, we have illuminated the lifelong development of precisely estimating another's gaze direction, and the psycho-physical process behind this. We have shown that gaze following continues to develop beyond infancy, and that individuals differ in their precision levels to localize the gaze direction of an agent. Our proposed process-level theory of gaze following modeled individual differences in precision as varying levels of uncertainty in the estimated gaze vectors. Consequently, we found that imprecision in gaze following relates to non-social vector following, as proposed by the model. Additionally, gaze following was linked to visual perspective-taking but no other aspects of ToM. The present research shows how precise and reliable measures and process models jointly inform each other and lead to a

more comprehensive understanding of the psychological phenomenon in question.

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## CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

## DATA AVAILABILITY STATEMENT

The gaze following task (<https://ccp-odc.eva.mpg.de/tango-demo/>) is open source (<https://github.com/ccp-eva/tango-demo>). The data sets generated during and/or analyzed during the current study are available in the following repository (<https://github.com/ccp-eva/gazecues-modeling>). All experiments and analyses were pre-registered prior to data collection (<https://osf.io/zjhsc/>).

## ETHICS STATEMENT

The study obtained ethical clearance by the MPG Ethics commission Munich, Germany, falling under an umbrella ethics application (Appl. No. 2021\_45). Informed consent was obtained from all individual participants or their legal guardians. The research adhered to the legal requirements of psychological research with children in Germany.

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## ENDNOTES

<sup>1</sup>As Jasso and Triesch (2006) put it: "There is a general agreement that tests of gaze following in the absence of targets are more stringent than with targets, because that eliminates the possibility that infants are simply following the target's saliency" (p. 2).

<sup>2</sup>Originally, we fit our models on a trial-by-trial basis with the following structure: performance ~ age + symmetricPosition + trialNr + (1 + symmetricPosition + trialNr | subjID). However, the Gaussian Process model was computationally heavy. Thus, we simplified the model structure, aggregated data on a subject level, and included only age as an effect. See [Supplementary information](#) for a comparison between the original and the here-reported model structures. The model predictions did not differ notably.

<sup>3</sup>In an additional analysis (see [Supplementary information](#)) analysis, we varied the parameters of our change point analysis and modified the number of allowed change points, the minimum number of data points between change points, and the polynomial order. When we allowed more explorative room, the models became more sensitive and added more fine-grained change points. The exact location of the change points varied slightly. However, the overall interpretation stayed the same, fitting our initial visual inspection: while early childhood was characterized by much

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change, adults showed a relatively stable level of imprecision, with a minor decay toward elderly adulthood. See *Supplementary information* for further detail.

<sup>4</sup>This model mirrors the logic of the TANGO programming code. In the online experiment, we read out the center point coordinates of the target and the agent's eyeball (i.e., the SVG coordinates), and then calculated a line between these two points: this was our gaze vector (acting in the functionally same way as a pupil angle). Knowing the eyeball radius, we calculated the point of intersection at which the gaze vector met the eyeball boundary. Finally, the agent's pupil moved from the center of the eyeball along the gaze vector to the intersection point. This way, the agent was animated to "look at" the target. In the gaze model, we assumed participants go through these steps in reverse order.

<sup>5</sup>In our screen-based study, this effect should decrease again towards the most outward sides. Since the computer screen has a natural border, trials in which the target lands furthest out to the left/right become slightly easier again. In these cases, the uncertainty about the pupil angle faces practically only the inner side (facing the center) of the screen, since the natural border of the screen limits where participants can click. In another adult sample with more trials, we could recover this pattern. For further elaboration, see *Supplementary information*.

<sup>6</sup>In an exploratory analysis, we simulated data for two more alternatives: a line-of-sight tracing model that assumed no inferential noise in the participants' gaze following ability, and a model building up on the line-of-sight tracing with added motor noise. Please note that these did not predict a U-shape pattern, since all target locations would be influenced by the motor noise equally. For further details, see *Supplementary information*.

<sup>7</sup>In an exploratory analysis, we compared children's imprecision levels in the TANGO task with animal versus human agents. Based on a GLMM analysis, we conclude that there was no evidence of a stable effect of stimulus choice. See *Supplementary information* for further detail.

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## Appendix A — Overview of Articles Included in the Dissertation

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- Meltzoff, A. N., Brooks, R., Shon, A. P., & Rao, R. P. N. (2010). "Social" robots are psychological agents for infants: A test of gaze following. *Neural Networks*, 23(8), 966–972. <https://doi.org/10.1016/j.neunet.2010.09.005>
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#### SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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## **Study III**

GAZE FOLLOWING ACROSS 17 COMMUNITIES

1

**1 A universal of human social cognition: Children from 17 communities process gaze in  
2 similar ways**

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**Abstract**

63 Theoretical accounts assume that key features of human social cognition are universal. Here we  
64 focus on gaze following, the bedrock of social interactions and coordinated activities, to test this  
65 claim. In a comprehensive cross-cultural study spanning five continents and 17 distinct cultural  
66 communities, we examined the development of gaze following in early childhood. We identified  
67 key processing signatures through a computational model that assumes that participants follow  
68 an individual's gaze by estimating a vector emanating from the eye center through the pupil.  
69 We found these signatures in all communities, suggesting that children worldwide processed  
70 gaze in highly similar ways. Absolute differences between groups were accounted for by a  
71 cross-culturally consistent relationship between children's exposure to touchscreens and their  
72 performance in the task. These results provide strong evidence for a universal process  
73 underlying a foundational socio-cognitive ability in humans that can be reliably inferred even  
74 in the presence of cultural variation in overt behavior.

75 A universal of human social cognition: Children from 17 communities process gaze in  
76 similar ways

## **Research Transparency Statement**

All authors declare no conflicts of interest. Preregistration: The hypotheses, methods and parts of the analysis plan were preregistered (<https://osf.io/tdsvc>) on March 12th, 2022, prior to data collection which began on March 18th, 2022. Additional analysis and deviations from the preregistration are reported in the Supplementary Material. Materials: All study materials are publicly available (<https://ccp-odc.eva.mpg.de/tango-cc/>). Data: All primary data are publicly available (<https://github.com/ccp-eva/gafo-cc-analysis/>). Analysis scripts: All analysis scripts are publicly available (<https://github.com/ccp-eva/gafo-cc-analysis/>).

## Introduction

Human socio-cognitive skills enable unique forms of communication and cooperation that provide a bedrock for cumulative culture and the formation of complex societies (Henrich, 2016; Heyes, 2018; Laland & Seed, 2021; Legare, 2019; Tomasello, 2020; Tomasello & Rakoczy, 2003; Wellman, 2014). The eyes are the proverbial “window to the mind” and eye gaze is essential for many social reasoning processes (Doherty, 2006; Emery, 2000; Shepherd, 2010). Others’ eye gaze is used to infer their focus of visual attention, which is a critical aspect of coordinated activities, including communication and cooperation (Langton et al., 2000; Richardson & Dale, 2005; Rossano, 2012; Scaife & Bruner, 1975; Sebanz et al., 2006; Tomasello et al., 2007).

The ability to follow gaze emerges early in development (Byers-Heinlein et al., 2021; Del Bianco et al., 2019; Gredebäck et al., 2010; Tang et al., 2023). The earliest signs of gaze following have been found in infants as young as four months (Astor et al., 2021; D'Entremont et al., 1997). Initially, infants rely more on head direction than actual gaze direction (Lempers et al., 1977; Michel et al., 2021). Throughout the first two years of life, children refine their abilities: they interpret gaze in mentalistic terms, for example, they follow gaze to locations outside their own

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101 visual field by moving around barriers (Moll & Tomasello, 2004). Importantly, individual  
102 differences in children's gaze following abilities predict later life outcomes, most notably  
103 communicative abilities (Carpenter et al., 1998). For example, gaze following at 10 months  
104 predicts language scores at 18 months of age (Brooks & Meltzoff, 2005). Difficulties with gaze  
105 following have been linked to developmental disorders, including Autism (Itier & Batty, 2009;  
106 Thorup et al., 2016, 2018). This work highlights the importance of gaze following as a  
107 foundational building block of human social interaction and its central place in theorizing.

108 A central assumption in the theoretical and empirical work discussed above is that,  
109 despite substantial variation in developmental contexts, gaze following works and develops in  
110 the same way across human societies (Tomasello, 2019). This assumption – despite being central  
111 to many developmental theories – is currently not supported by evidence. On the contrary,  
112 cross-cultural studies have revealed substantial diversity in socio-cognitive development  
113 (Dixson et al., 2018; Mayer & Träuble, 2013; Miller et al., 2018; Taumoepeau et al., 2019;  
114 Wellman, 2014). One of the very few cross-cultural studies also found differences in the  
115 likelihood to follow gaze between communities (Callaghan et al., 2011).

116 One potential source for this paradox lies in the reliance on aggregated measures in  
117 cross-cultural studies. Absolute differences in mean performance across communities are  
118 interpreted as a signal of different underlying cognitive processes. In the present study, we  
119 resolve this paradox by instead focusing on processing signatures that can be investigated  
120 independently of absolute community-level differences. This allows us to directly evaluate the  
121 empirical foundation of claims about universal features of human social cognition. To this end,  
122 we conducted a pre-registered, large-scale, cross-cultural study on the development of gaze  
123 following abilities to study potentially universal processing signatures.

124 The processing signatures were derived from a computational model that assumes that  
125 participants follow gaze by estimating a vector emanating from the eye center through the pupil  
126 (Prein, Maurits, et al., 2024). The key innovation of the model is that it explains how individuals

<sup>127</sup> may use the same cognitive process but still differ in their measured abilities. The process  
<sup>128</sup> always involves estimating a vector but also involves a degree of uncertainty because the eye  
<sup>129</sup> center is not directly observable. Individuals are assumed to differ in their level of uncertainty  
<sup>130</sup> with which they estimate the vector which causes differences in their observable behavior.  
<sup>131</sup> Importantly, the assumed process leaves a key signature in the data that is observable  
<sup>132</sup> independent of the absolute level of performance. In the present study, we therefore focus on  
<sup>133</sup> this signature instead of absolute levels of performance when evaluating the claim whether  
<sup>134</sup> there is evidence for a universal cognitive mechanism underlying gaze following.

<sup>135</sup> The 1377 participants who took part in the study lived in 17 different communities across  
<sup>136</sup> 14 countries and five continents (Fig. 1A, Tab. 1). These countries represent ~46% of the world's  
<sup>137</sup> population. Communities covered a broad spectrum of geographical locations, social and  
<sup>138</sup> political systems, languages, and subsistence styles (see Supplementary Material). This diversity  
<sup>139</sup> allowed us to overcome the common pitfall of cross-cultural studies that compare urban  
<sup>140</sup> communities from the Global North to rural communities from the Global South (Barrett, 2020).

**Table 1**  
*Participant demographics.*

Continent	Country	Community	N (male)	Age (range)	Language	Touchscreen exposure <sup>1</sup>
Americas	Argentina	Buenos Aires	105 (53)	4.72 (3.00 - 6.96)	Spanish (Rioplatense)	0.90
		Ocuilan	127 (63)	4.96 (2.57 - 6.95)	Spanish (Mexican)	0.77
	USA	Stanford	98 (54)	4.99 (2.52 - 7.90)	English (American)	0.98
Africa	Namibia	Hai  om	60 (38)	5.85 (2.74 - 8.34)	Hai  om	0.05

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Table 1 continued

Continent	Country	Community	N (male)	Age (range)	Language	Touchscreen exposure <sup>1</sup>
Africa	Namibia	Khwe	59 (24)	5.84 (3.38 - 8.63)	Khwedam	0.19
		Windhoek	39 (17)	5.69 (2.66 - 8.66)	English (Nigerian) <sup>2</sup>	0.95
	Nigeria	Akure	114 (54)	5.07 (2.57 - 7.33)	English (Nigerian)	0.91
	Rep. Congo	BaYaka	29 (13)	7.80 (3.94 - 10.56)	Yaka	0.00
	Congo	Bandongo	30 (11)	7.45 (3.50 - 10.95)	Lingala	0.00
		Nyabyeya	125 (62)	5.94 (2.67 - 8.92)	Kiswahili	0.34
	Zambia	Chimfunshi	22 (5)	5.98 (2.88 - 8.00)	Bemba	0.14
	Europe	Germany	Leipzig	4.88 (2.53 - 6.95)	German	0.89
	UK	Plymouth	70 (30)	6.02 (2.38 - 8.94)	English (British)	0.99
		Beijing	123 (62)	5.47 (2.69 - 8.48)	Mandarin	0.95
Asia	India	Pune	148 (73)	6.14 (3.06 - 8.83)	English (Indian) / Marathi	0.93

Table 1 continued

Continent	Country	Community	N (male)	Age (range)	Language	Touchscreen exposure <sup>1</sup>
	Türkiye	Malatya	85 (40)	5.02 (2.75 - 7.12)	Turkish	1.00
Oceania	New Zealand	Auckland	43 (19)	5.14 (2.81 - 8.75)	English (New Zealand)	0.95

*Note.* 1 Proportion of participants who have access to touchscreens according to parental questionnaire. 2 Local collaborators and piloting suggested that Nigerian English is suitable for Windhoek as well.

141

142 We used an animated picture book tablet task in which participants had to locate a  
 143 hidden object based on observing an agent's gaze. Children watched a balloon disappear behind  
 144 a hedge. An agent followed the trajectory of the balloon with their eyes (Fig. 1B). The key  
 145 dependent variable was the (im)precision with which children located the agent's focus of  
 146 attention, that is, the deviation between where the agent looked (where the balloon was) and  
 147 the child's response. We adapted visuals and audio instructions specifically for each of the 17  
 148 communities. Previous work demonstrated excellent individual-level measurement properties  
 149 for this task in a German sample (Prein, Kalinke, et al., 2024).

150

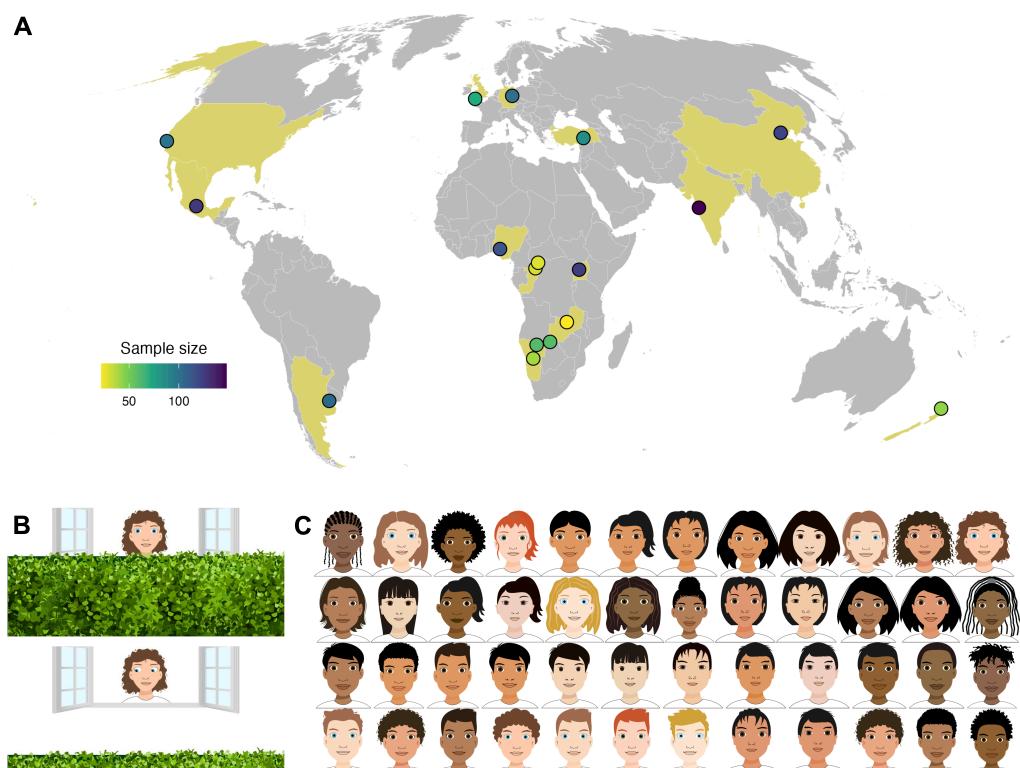
## Methods

### 151 Participants

152 A total of 1377 children between 2.38 and 10.95 years of age provided data for the study.  
 153 Children lived in 17 different communities, located in 14 different countries. Table 1 gives the

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**Figure 1**

(A) Data collection sites. Points show the approximate geographical location of the data collection sites, coloring shows the sample sizes. (B) Screenshots from the task. The upper scene depicts the start, and the lower scene depicts the choice phase in a test trial. Participants had to use the gaze of the agent to locate the balloon and touch the location on the hedge where they thought the balloon was. Agents, audio recordings and backgrounds were adapted to each community. (C) Drawings used as agents across communities.

154 sample size per community together with some basic demographic information. The  
155 recruitment strategy for each community is reported in the respective site descriptions. For  
156 some children, the exact birthday was unknown. In such cases, we set the birthday to the 30th  
157 of June of the year that would make them fall into the reported age category.

158 Data from children was only included in the study when they contributed at least four  
159 valid test trials. We also excluded the data from children with a diagnosed developmental  
160 disorder. In sum, in addition to the sample size reported above, 74 additional children  
161 participated in the study but did not contribute data. The main reasons for exclusion were:  
162 contribution of less than four valid test trials, technical failures, and missing or implausible  
163 demographic information (e.g., when the number of children living in the household was  
164 reported to be larger than the household itself or when the number of children reported to live  
165 in the household equaled the number of children younger than the child being tested). We did  
166 not exclude any participants for performance reasons. A detailed description of each data  
167 collection site and the way children were recruited can be found in the Supplementary Material.

168 **Setup and Procedure**

169 The task was implemented as a browser-based interactive picture book using HTML,  
170 CSS, and JavaScript. Participants saw animated agents on a touch screen device, listened  
171 to pre-recorded audio instructions and responded by touching the screen. In all communities, a  
172 research assistant, fluent in the local language(s), guided the child through the task.

173 Figure 1B shows a screenshot from the task. The task was introduced verbally by the  
174 assistant as the balloon game in which the participant would play with other children to find a  
175 balloon. On each trial, participants saw an agent located in a window in the center of the screen.  
176 A balloon fell down from its starting position just below the agent. The agent's gaze followed  
177 the trajectory of the balloon. That is, the pupils and the iris were programmed to align with the  
178 center of the balloon. Once the balloon had landed on the ground, the agent was instructed to  
179 locate it, that is, to touch the location on the screen where they thought the balloon was. On

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<sup>180</sup> each trial, we recorded the exact x-coordinate of the participant's touch.

<sup>181</sup> There were two types of training trials. In training 1 trials, the balloon fell down and  
<sup>182</sup> landed in plain sight. Participants simply had to touch the visible balloon. In training 2 trials,  
<sup>183</sup> the trajectory of the balloon was visible but it landed behind a small barrier (a hedge – see  
<sup>184</sup> Figure 1B). Thus, participants needed to touch the hedge where they saw the balloon land. Next  
<sup>185</sup> came test trials. Here, the barrier moved up and covered the balloon's trajectory. That is,  
<sup>186</sup> participants only saw the agent's eyes move, but not the balloon. They had to infer the location  
<sup>187</sup> of the balloon based on the agent's gaze direction. During training 1, training 2 and the first test  
<sup>188</sup> trial, children heard voice-overs commenting what happened on the screen. Critically, the agent  
<sup>189</sup> was described as wanting to help the child and always looking at the balloon.

<sup>190</sup> Children completed one training 1, two training 2 trials and 16 test trials. We excluded  
<sup>191</sup> the first test trial from the analysis because of the voice-over. Thus, 15 test trials were used in  
<sup>192</sup> the analysis below. Each child saw eight different agents (four male, four female). The agent  
<sup>193</sup> changed from trial to trial, with alternating genders. A coin toss before the first trial decided  
<sup>194</sup> whether the first agent was male or female. The order in which agents were shown was  
<sup>195</sup> randomized with the constraint that all agents had to be shown once until an agent was shown  
<sup>196</sup> again. The color of the balloon also changed from trial to trial in a random order, also with the  
<sup>197</sup> constraint that all colors appeared once before any one was repeated.

<sup>198</sup> The location (x-coordinate) where the balloon landed was determined in the following  
<sup>199</sup> way: The screen was divided in ten equally sized bins. On each trial, one of the bins was  
<sup>200</sup> randomly selected and the exact x-coordinate was randomly chosen within that bin.  
<sup>201</sup> Constraints were that the balloon landed in each bin equally often and the same bin appeared  
<sup>202</sup> no more than twice in a row.

<sup>203</sup> All children were tested with a touchscreen device with a size between 11 and 13 inch  
<sup>204</sup> equipped with a webcam. The data was either stored locally or sent to a server. In addition to

205 the behavioral data, we stored the webcam recording of the session for verification purposes.  
206 Community-specific adaptations were made by changing the visuals and the audio instructions  
207 (see Supplementary Material for details).

208 In addition to the gaze following task, caregivers responded to a short questionnaire  
209 about children's access to screens and touchscreens (binary answer) as well as the number of  
210 people, children and children younger than the focal child living in the household (numeric; see  
211 Supplementary Material for details). The numeric variables were scaled within community prior  
212 to inclusion into the regression models.

## 213 Analysis

### 214 Regression models

215 We used Bayesian Regression models fit in R (R Core Team, 2023) using the package  
216 `brms` (Bürkner, 2017) for all analyses except the cognitive models (see below). We used default  
217 priors built into `brms`. The dependent variable in all regression models was imprecision, that is,  
218 the absolute distance between the true location of the balloon (x-coordinate of its center) and  
219 the location where the participant touched the screen. We used a Log-normal distribution to  
220 model the data because the natural lower bound for imprecision is zero and the data was right  
221 skewed with a long tail. Numeric predictors that entered the models were scaled to have a mean  
222 of zero and a standard deviation of 1.

223 To analyse cross-cultural variation in performance, we used a cross-validation procedure  
224 (see e.g., Stengelin et al., 2023). In the Supplementary Material we give a detailed justification of  
225 this approach. For each community, we randomly sampled a data set that was 5/6 the size of the  
226 full data set (training data). Then, we fit the model to this training data and used the estimated  
227 model parameters to predict the remaining 1/6 of the data (testing data). We then compared the  
228 model predictions from the different models by computing the mean difference between the  
229 true and predicted imprecision, over all trials in the testing data set. We repeated the  
230 cross-validation procedure 100 times and computed the percentage of cases in which one model

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<sup>231</sup> outperformed the other. We compared three models: a null model assuming no systematic  
<sup>232</sup> community-level variation, a model assuming variation between communities and a model  
<sup>233</sup> assuming variation between communities and in developmental trajectories (see Supplementary  
<sup>234</sup> Material for model equations).

<sup>235</sup> To evaluate the processing signatures predicted by the cognitive model that trials in  
<sup>236</sup> which the balloon lands further away from the center lead to larger imprecision (see next  
<sup>237</sup> section for details), we fit a model predicting imprecision by age and target centrality (distance  
<sup>238</sup> of the landing position from the center in pixel/SVG units) with random intercepts for  
<sup>239</sup> participant and community and random slopes for target centrality within participant and  
<sup>240</sup> community (brms notation: `age + target_centrality +`  
<sup>241</sup> `(target_centrality | participant) + (age + target_centrality`  
<sup>242</sup> `| community)`).

<sup>243</sup> **Cognitive model**

<sup>244</sup> Recent computational work modeled gaze following as social vector estimation (Prein,  
<sup>245</sup> Maurits, et al., 2024). When following gaze, onlookers observe the location of the pupil within  
<sup>246</sup> the eye and estimate a vector emanating from the center of the eye through the pupil. The focus  
<sup>247</sup> of attention is the location where the estimated vectors from both eyes hit a surface (Fig. 3). It is  
<sup>248</sup> assumed that this estimation process has some uncertainty because the center of the eye is not  
<sup>249</sup> directly observable and that individuals vary in their level of uncertainty. As a consequence,  
<sup>250</sup> even though individuals use the same general process, they might differ in their absolute levels  
<sup>251</sup> of precision. Crucially, this process model predicts a clear performance signature in the gaze  
<sup>252</sup> following task: Trials in which the agent looks further away from the center should result in  
<sup>253</sup> lower levels of precision compared to trials in which the agent looks closer to the center. This  
<sup>254</sup> prediction is best understood by considering a similar phenomenon: pointing a torch light to a  
<sup>255</sup> flat surface. The width of the light beam represents each individual's level of uncertainty in  
<sup>256</sup> vector estimation. When the torch is directed straight down, the light beam is concentrated in a

<sup>257</sup> relatively small area. When the torch is rotated to the side, the light from one half of the cone  
<sup>258</sup> must travel further than the light from the other half to reach the surface. As a consequence,  
<sup>259</sup> the light is spread over a wider area (see Fig. 3).

<sup>260</sup> The model inversely models the process generating touches on the screen based on  
<sup>261</sup> observed eye movements and is defined as:

$$P(\theta|x_c, \alpha_l, \alpha_r) \propto P(x_c|\alpha_l, \alpha_r, \theta)P(\theta) \quad (1)$$

<sup>262</sup> Here,  $\theta$  represents an individual's cognitive ability to locate the focus of the agent's  
<sup>263</sup> attention,  $x_c$  represents the touched coordinate, and  $\alpha_l$  and  $\alpha_r$  correspond to the left and right  
<sup>264</sup> pupil angles (each defined as the angle between a line connecting the center of the eye to the  
<sup>265</sup> pupil and a line extended vertically downward from the center of the eye).

<sup>266</sup> The basic assumption in this model is that participants touch on the screen location  
<sup>267</sup> where they think the agent is looking. The true eye angles ( $\alpha_l$  and  $\alpha_r$ ) are not directly  
<sup>268</sup> observable and are estimated with noise, yielding  $\hat{\alpha}_l$  and  $\hat{\alpha}_r$ .

<sup>269</sup> Each touch  $x_c$  implies a "matched pair" of estimated pupil angles  $\hat{\alpha}_l$  and  $\hat{\alpha}_r$ , with the  
<sup>270</sup> constraint that the lines extended along those two angles meet at the precise location of where  
<sup>271</sup> the target is believed to be. As a consequence, we can rewrite the likelihood function of the  
<sup>272</sup> model as:

$$P(x_c|\alpha_l, \alpha_r, \theta) \propto P(\hat{\alpha}_l, \hat{\alpha}_r|\alpha_l, \alpha_r, \theta)P(x_c) \quad (2)$$

<sup>273</sup>  $P(x_c)$  is a prior over potential target locations. Because the target was last visible in the  
<sup>274</sup> screen and because the agent was located in the center, we assumed that participants have an a  
<sup>275</sup> priori expectation that the target will land close to the middle. We estimated the strength of this

<sup>276</sup> center bias (*i.e.*, the standard deviation of a Normal distribution around the screen center) based  
<sup>277</sup> on the data:  $P(x_c) \sim \mathcal{N}(960, \sigma^p)$ .

<sup>278</sup> The primary inferential task for participants is therefore to estimate the pupil angles ( $\hat{\alpha}_l$   
<sup>279</sup> and  $\hat{\alpha}_r$ ), that is, to sample from the term  $P(\hat{\alpha}_l, \hat{\alpha}_r | \alpha_l, \alpha_r, \theta)$ . Here, we assumed that the pair of  
<sup>280</sup> estimated pupil angles were sampled from a probability distribution which is the product of two  
<sup>281</sup> Normal distributions of equal variance,  $\sigma_v$ , centered on the true pupil angles:

$$P(\hat{\alpha}_l, \hat{\alpha}_r | \alpha_l, \alpha_r, \theta) \propto \phi(\hat{\alpha}_l; \alpha_l, \sigma_v) \phi(\hat{\alpha}_r; \alpha_r, \sigma_v), \quad (3)$$

<sup>282</sup> Here,  $\sigma_v$  determines the level of accuracy with which participants estimated the pupil  
<sup>283</sup> angles, and it is thus the component of the model that defines  $\theta$ . Smaller values of  $\sigma_v$  result in a  
<sup>284</sup> narrow distribution around the pupil angle, making touches far away from the target less likely.  
<sup>285</sup> Conversely, larger values for  $\sigma_v$  lead to a wider distribution, making touches far away from the  
<sup>286</sup> target more likely. To circle back to the analogy introduced above,  $\sigma_v$  corresponds to the width  
<sup>287</sup> of the light beam. Thus, the goal of the model was to estimate participant-specific values for  $\sigma_v$ :  
<sup>288</sup>  $\sigma_{v_i}$ . For more details on how  $\sigma_{v_i}$  was estimated, see the Supplementary Material.

<sup>289</sup> To summarize, the model assumes that participant's touches are generated by a process  
<sup>290</sup> that relies on noisy estimates of the agent's gaze direction. The precision, with which the gaze  
<sup>291</sup> direction is estimated, varies between participants and increases with development.

<sup>292</sup> As stated above, the key signature prediction of the model is that precision decreases  
<sup>293</sup> when the balloon lands further away from the center. This pattern, however, also arises when  
<sup>294</sup> participants ignore the agent's gaze completely and instead follow simple heuristics. We  
<sup>295</sup> implemented these heuristics as alternative models and directly compared them to the gaze  
<sup>296</sup> estimation model. According to the center bias model, participants always try to touch in the  
<sup>297</sup> center of the screen:  $P(x_c) \sim \mathcal{N}(960, 160)$  (960 is the x-coordinate of the center and 160 is the

<sup>298</sup> width of the balloon). According to the random guessing model, they randomly touch  
<sup>299</sup> coordinates on the screen:  $P(x_c) \sim \mathcal{U}(0, 1920)$ .

<sup>300</sup> The cognitive models were implemented in the probabilistic programming language  
<sup>301</sup> `webpp1` (Goodman & Stuhlmüller, 2014). All models were run separately for each community.  
<sup>302</sup> Information on the prior distributions for all model parameters can be found in the associated  
<sup>303</sup> online repository. We compared models based on the marginal likelihood of the data for each  
<sup>304</sup> model, which represents the likelihood of the data while averaging over the prior distribution  
<sup>305</sup> on parameters. The pair-wise ratio of marginal likelihoods for two models is known as the  
<sup>306</sup> Bayes Factor. Bayes Factors are a quantitative measure of the predictive quality of a model,  
<sup>307</sup> taking into account the possible values of the model parameters weighted by their prior  
<sup>308</sup> probabilities. The incorporation of the prior distribution over parameters in the averaging  
<sup>309</sup> process implicitly considers model complexity: models with more parameters typically exhibit  
<sup>310</sup> broader prior distributions over parameter values and broader prior distribution can attenuate  
<sup>311</sup> the potential gains in predictive accuracy that a model with more parameters might otherwise  
<sup>312</sup> achieve (Lee & Wagenmakers, 2014).

## <sup>313</sup> Results

### <sup>314</sup> Cross-cultural variation in development

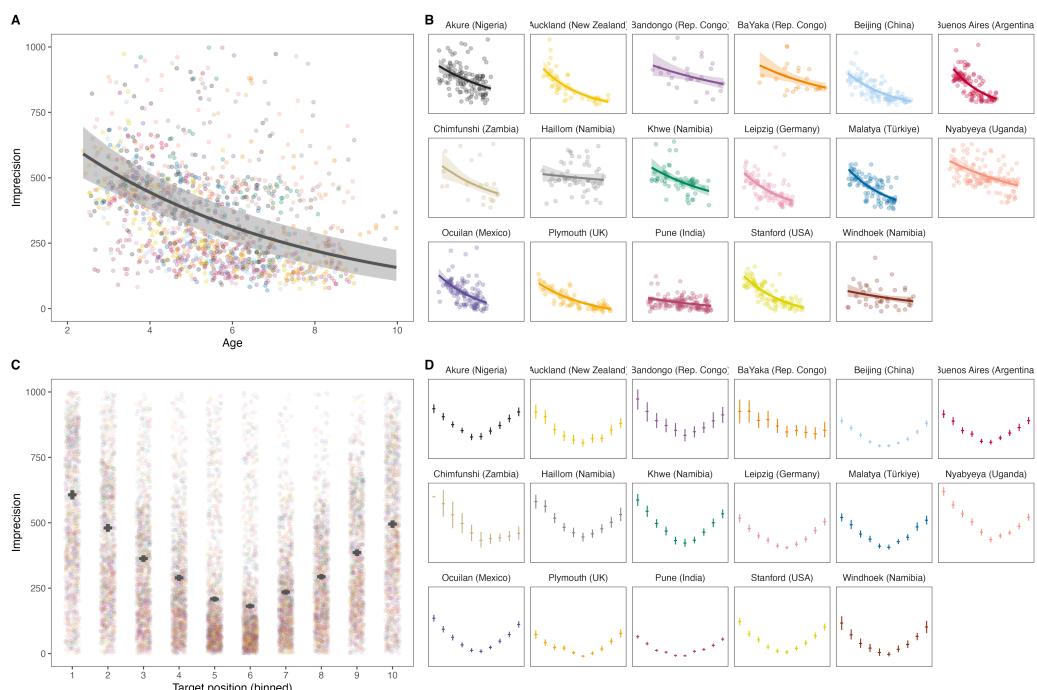
<sup>315</sup> As the first step, we investigated developmental improvements, that is, how children  
<sup>316</sup> become more precise at estimating the target location with age. Across all 17 communities, we  
<sup>317</sup> found a substantial increase in average levels of precision with age (fixed effect of age:  $\beta = -0.30$ ,  
<sup>318</sup> 95% Credible Interval (CrI) (-0.40 - -0.21); range of community-level (random) effects:  $\beta_{min} =$   
<sup>319</sup> -0.06, 95% CrI (-0.18 – 0.05) to  $\beta_{max} = -0.59$ , 95% CrI (-0.71 – -0.48)).

<sup>320</sup> Nevertheless, there were also marked differences between communities (see Fig. 2A).  
<sup>321</sup> The cross-validation procedure found that a model assuming cross-cultural variation in average  
<sup>322</sup> performance as well as cross-cultural variation in developmental trajectories outperformed  
<sup>323</sup> simpler models – assuming no variation in the shape of developmental trajectories or no

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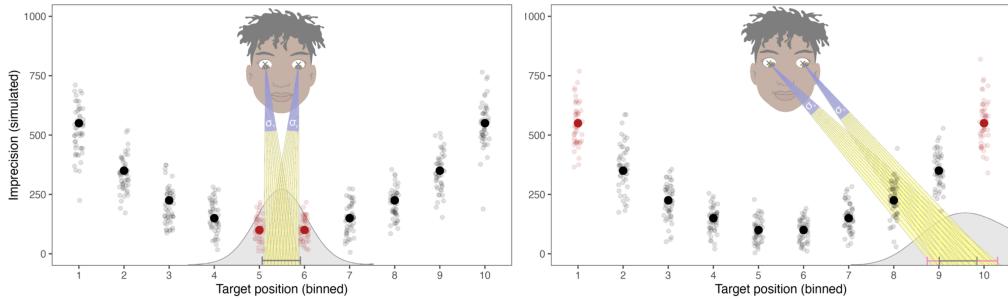
324 variation between settings at all – in 98% of cases.  
 325 Average differences in precision between communities were small compared to  
 326 differences between individuals: communities did not form homogeneous clusters but largely  
 327 overlapping distributions in that some individuals from communities with a lower average level  
 328 of precision performed better compared to some individuals from a setting with a very high  
 329 average level of precision. Similarly, in all communities, some 4-year-olds outperformed  
 330 children two years older than them (see Fig. 2A). The lack of adequate individual-level  
 331 measurement instruments in previous large-scale developmental cross-cultural studies made it  
 332 impossible to contrast these perspectives.



**Figure 2**

A) Developmental trajectory across and B) by community. The developmental trajectories are predicted based on a model of the data aggregated for each participant. C) Performance by target location on the screen across, and D) by community. Each bin covers 1/10th of the screen. Points show means, and error bars 95% confidence intervals for the data within that bin aggregated across participants. Transparent dots in A) and C) show aggregated data for each individual.

333 **Universal processing signatures**



**Figure 3**

*Graphical illustration of the cognitive model. Individuals infer the target of an agent's attention by estimating a vector based on the position of the pupils within the eyes. This process is noisy, illustrated by the different vectors (transparent lines). Individuals differ in their level of precision (indicated by sigma). For a given level of precision, the further the target lands from the center of the screen, the less precise the model predicts individuals to be. Solid and transparent dots show simulated means and individual data points to illustrate the predicted effect of target position.*

334 The key processing signature predicted by the cognitive model was that precision should  
 335 decrease when the balloon landed further away from the center. This signature was clearly  
 336 visible across all 17 communities (fixed effect for target centrality:  $\beta = 0.47$ , 95% CrI (0.40 –  
 337 0.54); range of community-level (random) effects:  $\beta_{min} = 0.58$ , 95% CrI (0.51 – 0.66) to  $\beta_{max} =$   
 338 0.16, 95% CrI (-0.01 – 0.33)). Visualization of the data showed the predicted u-shaped pattern in  
 339 all communities (see Fig. 2B). When we compared the focal vector-based gaze estimation model  
 340 described above to the alternative center bias and random guessing models, we found  
 341 overwhelming support for the gaze estimation model ( $\min BF_{10} > 100\,000$  for comparisons  
 342 with both alternative models, see Supplementary Materials) in every community.

343 **Predictors of variation**

344 We used the caregiver questionnaire to explain community- and individual-level  
 345 variation. On an individual level, we found that children with access to touchscreen devices had  
 346 higher levels of precision ( $\beta = -0.14$ , SE = 0.04, 95% CrI = -0.21 – -0.07). This effect was  
 347 consistent across communities in that allowing the effect of access to touchscreens to vary  
 348 across communities did not improve model fit (see Supplementary Material). On a community

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349 level, we also saw that average performance was lowest in communities in which touchscreen  
350 devices were the least frequent (community-level correlation between age-corrected  
351 imprecision and proportion of children with access to touchscreens:  $r = -0.90$ , 95% CI =  $-0.96 -$   
352  $-0.74$ ). Thus, familiarity with the device used for data collection likely explains variation  
353 between communities. Children with more touchscreen experience were probably better at task  
354 handling and thus more likely to precisely touch the location they inferred the agent to look at.

355 However, there was substantial variation between individuals that could not be  
356 explained by differential exposures to touchscreens alone. For example, in Malatya (Türkiye)  
357 where 100% of children had access to touchscreens there was still substantial variation between  
358 individuals (see Fig.1B). This strongly indicates that other factors likely contributed to individual  
359 differences. Social interaction has been highlighted as an important driver of social-cognitive  
360 development (Barresi & Moore, 1996; Carpendale & Lewis, 2020; Perner et al., 1994; Rakoczy,  
361 2022; e.g., Tomasello, 2019) and thus we hypothesized (and pre-registered) that more  
362 opportunities for social interaction – approximated by living in larger households with more  
363 children – would be associated with higher levels of precision. When predicting performance  
364 by relative opportunities for social interactions within a community – while accounting for  
365 absolute differences and the prevalence of touchscreens – we found no strong associations  
366 between any of the demographic indicators and performance (see Supplementary Material).

**367 Discussion**

368 Following and understanding gaze is a foundational building block of human social  
369 cognition (Langton et al., 2000; Richardson & Dale, 2005; Rossano, 2012; Scaife & Bruner, 1975;  
370 Sebanz et al., 2006; Tomasello et al., 2007). A substantial body of work has explored the  
371 developmental onset of gaze following in a few selected cultural communities (Byers-Heinlein  
372 et al., 2021; Gredebäck et al., 2010; Moore, 2008; Tang et al., 2023). The data reported here  
373 provides strong evidence that children from a large and diverse set of communities process  
374 others' gaze in similar ways. We found key performance signatures predicted by a model

375 treating gaze following as a form of social vector estimation process across all 17 communities.  
376 With the focus on individual-level processing signatures, the study goes beyond previous  
377 studies on gaze following – focused on the onset of gaze following in infancy (Callaghan et al.,  
378 2011; Hernik & Broesch, 2019) – as well as comprehensive cross-cultural studies that compared  
379 average developmental trajectories (Blake et al., 2015; House et al., 2020; Kanngiesser et al.,  
380 2022; Van Leeuwen et al., 2018).

381 The cognitive processes underlying gaze following might be rooted in humans' evolved  
382 cognitive architecture, which is – presumably – later refined during social interaction (Astor et  
383 al., 2020; Movellan & Watson, 2002; Senju et al., 2015). The phylogenetic roots of these processes  
384 might possibly lie much deeper as primates from a wide range of species follow gaze (Itakura,  
385 2004; Kano & Call, 2014; Rosati & Hare, 2009; Tomasello et al., 1998). Yet, similarities in overt  
386 behavior do not imply the same underlying cognitive processes. The present study defines clear  
387 performance signatures that can be explored in other species to test such evolutionary  
388 hypotheses.

389 Our study combined precise individual-level cognitive measurement and individual-level  
390 assessment of experience (here: touchscreen exposure) in a large and diverse sample to directly  
391 investigate the impact of specific cultural experiences on developmental outcomes. Instead of  
392 establishing universality by maximizing the cultural distance between two or three tested  
393 communities (Norenzayan & Heine, 2005), this large-scale cross-cultural approach treats  
394 children's cultural experience at scale, shedding light on the big “middle ground” of children's  
395 cultural experience (Barrett, 2020).

396 The study has important limitations. The fact that performance in the task was  
397 correlated with exposure to touchscreens might have overshadowed other sources of variation.  
398 However, we think it is an important innovation that we were able to account for this effect.  
399 Most developmental cross-cultural studies do not even question the portability of their  
400 measurement instruments. Importantly, the key result that the processing signatures were seen

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401 in all communities, is immune to this finding. The potential that lies in the otherwise precise  
402 individual-level measurement that the task achieves is largely unexploited. The questionnaire  
403 items only offer a very coarse picture into children's actual lived experiences. Whilst household  
404 size was a useful proxy for regular social interaction opportunities, the measure does not  
405 directly measure the factors that previous work has suggested to be related to the development  
406 of gaze following in younger children, such as attachment quality or the use of gaze in early  
407 communicative interactions (Astor et al., 2020; Movellan & Watson, 2002; Senju et al., 2015).  
408 Future work could increase the resolution with which everyday experiences in children from  
409 diverse communities are recorded to compare the drivers behind social-cognitive development  
410 as we observe it. Recent work in the field of language acquisition has shown how technological  
411 innovations allowed for direct recording of social interactions across communities which can be  
412 used to close this explanatory gap (Bergelson et al., 2023; Donnelly & Kidd, 2021).

413 In sum, our work pioneers an approach that introduces computational modeling and  
414 precise individual-level measurement to the cross-cultural study of cognitive development. This  
415 approach allowed us to test for universals in the human cognitive architecture rather than just  
416 overt behavior. As such, it can serve as a blueprint for future research on a broad spectrum of  
417 cognitive abilities and offers a much-needed empirical foundation for theories on the nature of  
418 the human mind. Children from diverse communities deploy similar cognitive processes in  
419 interpreting gaze, pointing to a universal foundation of basic social cognition, which is refined  
420 during development.

421

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## **Study IV**

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# 1 Measuring variation in gaze following across communities, ages, and individuals – a 2 showcase of the TANGO-CC

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**Abstract**

97 Cross-cultural studies are crucial for investigating the cultural variability and universality of  
98 cognitive developmental processes. However, cross-cultural assessment tools in cognition  
99 across languages and communities are limited. This paper describes a gaze following task  
100 designed to measure basic social cognition across individuals, ages, and communities  
101 (TANGO-CC). The task was developed and psychometrically assessed in one cultural setting  
102 and, with input of local collaborators, adapted for cross-cultural data collection. Minimal  
103 language demands and the web-app implementation allow fast and easy contextual adaptations  
104 to each community. The TANGO-CC captures individual- and community-level variation and  
105 shows good internal consistency in a data set from 2.5- to 11-year-old children from 17 diverse  
106 communities. Within-community variation outweighed between-community variation. We  
107 provide an open-source website for researchers to customize and use the task  
108 (<https://ccp-odc.eva.mpg.de/tango-cc>). The TANGO-CC can be used to assess basic social  
109 cognition in diverse communities and provides a roadmap for researching community-level and  
110 individual-level differences across cultures.

111        *Keywords:* cross-cultural psychology, social cognition, gaze following, individual  
112 differences, reliability

113        Word count: XXX

114     **Measuring variation in gaze following across communities, ages, and individuals – a**  
115         **showcase of the TANGO-CC**

116             **Introduction**

117         For decades, researchers have advocated for more diverse samples in psychological  
118         research and cautioned against relying solely on convenience samples from the Global North  
119         (Arnett, 2008; Henrich et al., 2010; Lillard, 1998). Despite numerous calls for change, the samples  
120         reported in major psychology journals still lack diversity (Apicella et al., 2020; Gutchess &  
121         Rajaram, 2023; Thalmayer et al., 2021). This hinders progress in theory building and testing: we  
122         cannot draw inferences about universal and variable aspects of the human cognitive system  
123         from data collected exclusively in one single community (Krys et al., 2024). While this sampling  
124         bias is often discussed within adult psychology, it is equally relevant to developmental  
125         psychology (Nielsen et al., 2017). Early experiences shape the way children think about and  
126         interact with the world and an ontogenetic perspective is needed to explore the foundational  
127         aspects of human behavioral diversity (Amir & McAuliffe, 2020; Broesch et al., 2023; Liebal &  
128         Haun, 2018; Torréns et al., 2023).

129         There are numerous challenges with collecting cross-cultural, developmental data (Amir  
130         & McAuliffe, 2020; Broesch et al., 2023). Cross-cultural studies need reliable and valid measures  
131         to capture variation between communities and/or individuals systematically. Even though this  
132         applies to all areas of cognitive development, we focus on social cognition in this paper.

133         Social cognition refers to how an individual processes information in social situations  
134         which allows them to understand and predict others' behavior (Adolphs, 1999; Decety, 2020;  
135         Frith & Frith, 2007; Zeigler-Hill et al., 2015). If, in theory, stimuli used in social cognition tasks  
136         should relate to people's everyday experiences, then tasks themselves should be tuned to the  
137         features of specific communities. Indeed, task performance can be diminished when stimuli do  
138         not reflect the characteristics of the participants' communities (Peña, 2007). For example,  
139         Elfenbein and Ambady (2002) found better emotion recognition for members of the same

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<sup>140</sup> national, ethnic, or regional group. Selcuk et al. (2023) concluded that children often attribute  
<sup>141</sup> mental states more accurately and more frequently to individuals from the same community.

<sup>142</sup> From a psychometric perspective, the situation looks dire. Studies on social cognition  
<sup>143</sup> with US-American and European samples rarely report psychometric information (for a review,  
<sup>144</sup> see Beaudoin et al., 2020), and the picture further deteriorates when we look at cross-cultural  
<sup>145</sup> social cognition tasks (Bourdage et al., 2023; Hajdúk et al., 2020; Waschl & Chen, 2022). Thus, it  
<sup>146</sup> is already challenging to find reliable and valid tasks that have measurement sensitivity to  
<sup>147</sup> detect individual differences within one community, let alone tasks that do so across different  
<sup>148</sup> communities. In this paper, we describe the construction and psychometric evaluation of a  
<sup>149</sup> cross-cultural measure of basic social cognition (gaze following) in children as a concrete  
<sup>150</sup> example of how to address this problem.

<sup>151</sup> The approaches that researchers can take to collect cross-cultural data lie on a  
<sup>152</sup> continuum: the decision for a specific method partly depends on whether researchers aim to  
<sup>153</sup> increase the *depth* (culture specificity) or *breadth* (standardization across multiple communities)  
<sup>154</sup> of their work (Amir & McAuliffe, 2020). At one extreme, researchers translate the psychological  
<sup>155</sup> construct into a separate design or task for each community (termed “assembly”; He and Vijver  
<sup>156</sup> (2012), Waschl and Chen (2022)). While this approach allows greater flexibility and sensitivity to  
<sup>157</sup> cultural differences, it might not be feasible to study a multitude of communities as it becomes  
<sup>158</sup> too demanding and time-consuming. Furthermore, the results are limited to each community  
<sup>159</sup> and absolute task scores might not be comparable across communities. A study following this  
<sup>160</sup> approach is Wefers et al. (2023) who investigated how cultural variations in parenting styles  
<sup>161</sup> modulated infants’ responses to disruptions in social interactions. While studies in the Global  
<sup>162</sup> North often apply the Still-Face Paradigm to assess infants’ reactions to unresponsive partners,  
<sup>163</sup> Wefers et al. (2023) reasoned that this paradigm might not capture infants’ everyday interaction  
<sup>164</sup> routines in communities with proximal (*i.e.*, emphasis on body stimulation) parenting styles. By  
<sup>165</sup> developing the novel No-Touch Paradigm, they found that indeed infants’ responses to

<sup>166</sup> unresponsive partners were modulated by the cultural context in which they grew up: Kichwa  
<sup>167</sup> infants from rural Ecuador showed stronger reactions to unresponsive partners in the No-Touch  
<sup>168</sup> Paradigm compared to the Still-Face Paradigm, while reactions of urban German infants  
<sup>169</sup> differed less in both paradigms.

<sup>170</sup> At the other extreme, researchers use the same standardized procedure across diverse  
<sup>171</sup> communities, potentially providing a simple translation or modification of stimuli to ensure  
<sup>172</sup> they are culturally appropriate (termed “adoption” and “adaptation”, respectively; Waschl &  
<sup>173</sup> Chen (2022)). This approach is less sensitive to each community’s unique characteristics but  
<sup>174</sup> renders quantitative comparisons of data more feasible. An example following this approach is  
<sup>175</sup> the Multilingual Assessment Instrument for Narratives (MAIN; (Gagarina et al., 2012)), which  
<sup>176</sup> assesses narrative abilities in mono- and multilingual children. Extensive piloting and  
<sup>177</sup> adaptation of MAIN materials ensured that the instrument is culturally appropriate, robust, and  
<sup>178</sup> suitable for cross-linguistic comparisons (Gagarina et al., 2012), and new and revised language  
<sup>179</sup> versions are continuously added to the MAIN database (Gagarina & Lindgren, 2020).

<sup>180</sup> The present paper aims to describe the development and psychometric properties of a  
<sup>181</sup> social cognition task that can be adapted to diverse communities. On the continuum described  
<sup>182</sup> above, our task lies more toward standardized approaches but allows for some customization of  
<sup>183</sup> the stimuli to each local community. The task focuses on one of the most fundamental  
<sup>184</sup> social-cognitive abilities: gaze following, that is, the ability to identify the attentional focus of  
<sup>185</sup> another agent. Gaze following develops early in infancy (Del Bianco et al., 2019; Tang et al.,  
<sup>186</sup> 2024) and contributes to social learning, communication, and collaboration (Bohn & Köymen,  
<sup>187</sup> 2018; Hernik & Broesch, 2019; Shepherd, 2010; Tomasello et al., 2007). While the question of  
<sup>188</sup> how social-environmental and cultural factors impact gaze following was recently posed as one  
<sup>189</sup> of the big open questions in gaze following research (Astor & Gredebäck, 2022), studies focusing  
<sup>190</sup> on cultural variations of gaze following are rare. Callaghan et al. (2011) investigated gaze  
<sup>191</sup> following behind barriers in 12- and 17-month-olds from rural Canada (n = 35), Peru (n = 38),

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192 and India ( $n = 65$ ). In their setup, an agent looked at a toy behind (experimental condition) or a  
193 sticker in front of (control condition) a barrier, and children's crawling toward the barrier to  
194 follow the agent's gaze was assessed. While the absolute crawling rates differed across  
195 communities, children in all three communities crawled more often to gain visual access when  
196 the agent looked at an object behind the barrier than in front of it. Hernik and Broesch (2019)  
197 studied 22 infants between 5 to 7 months of age from Vanuatu and used an eye-tracking  
198 procedure displaying a local actor looking at one of two objects. Even though face-to-face  
199 interactions are less common in parent-child interactions in Vanuatu than in Western  
200 communities, the result patterns of gaze following in Ni-Vanuatu infants resembled those of  
201 their Western counterparts: infants from Vanuatu followed the agent's gaze to the target object  
202 only when preceded by infant-directed, and not adult-directed, speech. While these two studies  
203 point towards potential cross-cultural stability of gaze following, the lack of psychometrically  
204 evaluated tasks and the small number of communities studied limit the generalizability of these  
205 findings and – more importantly – does not allow for studying individual-differences. A more  
206 comprehensive cross-cultural study on gaze following was recently conducted by Bohn et al.  
207 (2024). The researchers tested the universality of gaze following by studying 17 different  
208 communities on five continents and found evidence for a similar processing mechanism across  
209 communities.

210 The task presented in this manuscript was developed for the study by Bohn et al. (2024)  
211 and is based on a previously established gaze-following task called 'TANGO' (Task for  
212 Assessing iNdividual differences in Gaze understanding - Open) by Prein et al. (2023). The  
213 TANGO measures how precisely participants locate an agent's attentional focus. It reliably  
214 measured individual differences in a German child sample and an English-speaking remote  
215 adult sample (Prein et al., 2023). However, we cannot claim the task's generalizability and  
216 reliability based on a mono-cultural sample. This paper showcases the TANGO-CC (TANGO –  
217 Cross-Cultural), a standardized gaze following task that has been adapted to 13 languages and  
218 even more communities, and evaluates its psychometric properties by leveraging a large and

<sup>219</sup> diverse data set of 2.5- to 11-year-olds from 17 diverse communities (Bohn et al., 2024). We  
<sup>220</sup> describe the task's development and provide a tutorial for the open-source website  
<sup>221</sup> (<https://ccp-odc.eva.mpg.de/tango-cc/>).

<sup>222</sup> **Task development**

<sup>223</sup> **Approach**

<sup>224</sup> The TANGO-CC was implemented in Leipzig, Germany, and thoroughly assessed in  
<sup>225</sup> terms of reliability and validity (Prein et al., 2023). During this process, the cross-cultural  
<sup>226</sup> adaptation of the task was prepared by a team of cross-cultural psychologists and cognitive  
<sup>227</sup> scientists. In this paper, we assess the TANGO-CC's measurement quality (*i.e.*, variability and  
<sup>228</sup> reliability) across 17 diverse communities by analyzing the data set from Bohn et al. (2024). In  
<sup>229</sup> the following, we describe the different steps in detail.

<sup>230</sup> The TANGO-CC is a screen-based task that measures the imprecision with which  
<sup>231</sup> participants locate a balloon by following an agent's gaze (see Figure 1). Participants click or  
<sup>232</sup> touch the location on the screen where they believe the balloon to be. Precision is measured as  
<sup>233</sup> the distance between the participant's click on the screen and the balloon's real position.

<sup>234</sup> During the task development, we decided to implement the task's main functionality  
<sup>235</sup> independently of the task's appearance. We programmed a function that calculates the x and y  
<sup>236</sup> coordinates of where the agent's pupil and iris should move to follow the balloon, given the  
<sup>237</sup> eyes' and balloon's original positions and measures. As the measures of the eyes and balloon  
<sup>238</sup> are read out dynamically from the image on screen, stimuli can be easily adapted and  
<sup>239</sup> exchanged (*i.e.*, no coordination values for animation are hard-coded into the task's source  
<sup>240</sup> code). After having programmed this "backbone" functionality of the task (*i.e.*, animate the eyes  
<sup>241</sup> so that they follow the balloon), we added the task's audio instructions and superficial  
<sup>242</sup> appearance (e.g., background scene, hedge, agent faces).

<sup>243</sup> This basic version of the TANGO was psychometrically evaluated in a German child

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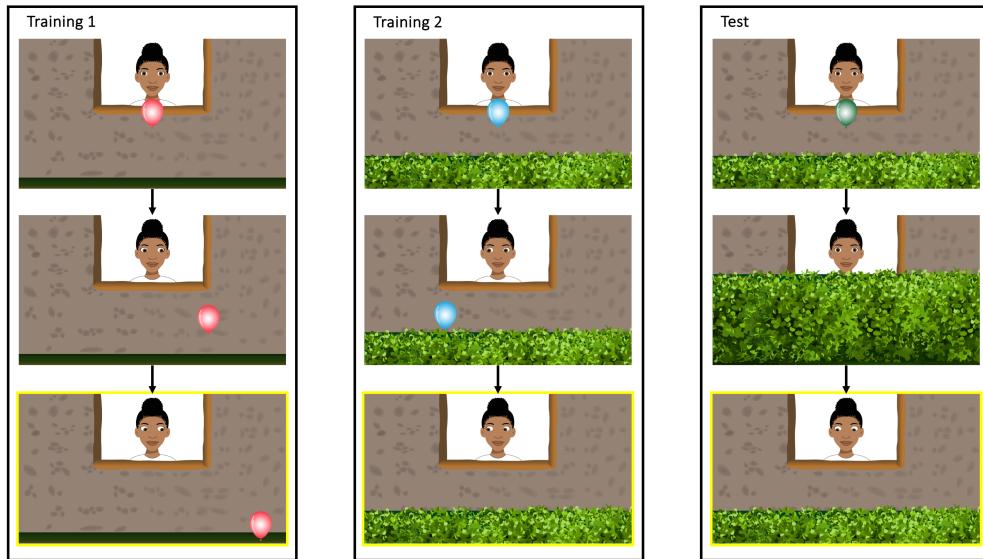
244 sample and an English-speaking remote adult sample and was found to be highly reliable and  
245 valid (Prein et al., 2023). While children became more precise in locating the agent's attentional  
246 focus with age, individuals differed across all age groups and showed no floor- or ceiling effects.  
247 In the Leipzig sample, performance in the TANGO was weakly related to factors of children's  
248 daily social environment and could predict children's receptive vocabulary 6 months later. In a  
249 computational cognitive model, Prein et al. (2024) described gaze following as a form of social  
250 vector following and empirically found that performance in the TANGO was related to  
251 children's non-social vector following and visual perspective-taking abilities. These connections  
252 to related constructs indicate the task's convergent validity in the German child sample.

253 To adapt the task for cross-cultural data collection, we generated a set of human cartoon  
254 faces and background scenes with input from local researchers and research assistants. The  
255 stimulus pool was adjusted and expanded until the researchers and research assistants from  
256 each target community judged the selected stimuli to be representative of the local population  
257 and typical accommodation (see Figure 2). Audio instructions were translated from English or  
258 German into the corresponding local language(s). By back-translating these instructions, we  
259 ensured the original meaning did not change. Sometimes, specific words were slightly modified  
260 in the target language (e.g., "bush" instead of "hedge") to ensure that all participants understood  
261 the instructions well. Based on these adaptations, the TANGO-CC could be applied in 17  
262 communities and 13 different languages (Bohn et al., 2024). In the following, we describe how  
263 researchers can use and customize the TANGO-CC in more detail.

264 **Features of the TANGO-CC**

265 ***Trials***

266 The task consists of three different trial types: training 1, training 2, and test trials (see  
267 Figure 1). In every trial, participants see an agent (boy or girl) looking out of a house with a  
268 balloon (red, blue, green, or yellow) in front of them. The balloon falls down to the ground. The  
269 eyes of the agent follow the movement of the balloon in a way that the balloon center and the



**Figure 1**

**Screenshots of the trials.** In training 1, an agent looks at a balloon that falls to the ground, and participants have to respond by clicking/touching the balloon. In training 2, the balloon falls behind the hedge while its flight is still visible. Participants respond by clicking the hedge where they think the balloon is. In test trials, the balloon's movement and final position are covered by a hedge, and participants respond by clicking the hedge. In the task, all movements are smoothly animated (no still pictures). Yellow frames indicate the time point when participants respond (only illustrative, not shown during the task).

270 pupil center always align. Depending on the trial type, participants have different visual access  
 271 to the balloon's position. In training 1, participants see the full trajectory of the balloon and  
 272 directly have to click the balloon itself. In training 2, participants see most of the balloon's  
 273 movement, but a hedge covers the final location. In test trials, a hedge grows at the beginning  
 274 of the trial and participants see neither the movement nor the final position of the balloon. The  
 275 first trial of each type contains an audio description of the presented events (see Supplements).  
 276 Notably, the instructions explicitly state that the agent is looking at the balloon.

277 The outcome variable is the distance between the participant's click and the balloon's  
 278 center. Trials can be completed quickly and efficiently so that children can complete 15 trials  
 279 within 10 minutes, and few children fail to complete the task. By using self-explanatory

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280    animations, language demands are kept to a minimum. The task uses simple audio instructions,  
281    which makes the task accessible to children from different age groups, and no reading skills are  
282    required. There is no feedback during the task to prevent learning effects across trials.

### 283    ***Randomization***

284    The order of the agents, balloon colors (red, yellow, green, blue), and balloon positions  
285    are each randomized independently. For the balloon positions, the entire width of the screen  
286    (1920 in “SVG units”) is divided into ten bins. Exact coordinates (value between 0 for the far left  
287    and 1920 for the far right) within each bin are then randomly generated. The number of  
288    repetitions for each agent, balloon color, and balloon bin is calculated based on the total number  
289    of trials and the number of unique agents, balloon colors, and bins, respectively. All agents,  
290    balloon colors, and bins appear equally often and are not repeated in more than two consecutive  
291    trials. If the total number of trials is not divisible by the number of unique elements, some  
292    elements (*i.e.*, some agents, balloon colors, bins) are randomly repeated to make up for the  
293    remainder.

### 294    ***Cross-cultural customization***

295    When researchers visit the TANGO–CC’s website  
296    (<https://ccp-odc.eva.mpg.de/tango-cc/>), they can select the language for audio instructions  
297    which are currently available for 13 different languages and five more dialects (see Table 1). To  
298    add a new language, researchers have two options: (1) for using their own audio instructions in  
299    the offline version of the task, researchers can download the task, exchange the audio  
300    instructions in the dist folder (in the folder sounds > custom) and select “Custom” in the  
301    language drop-down menu. For detailed instructions, see the TANGO–CC’s manual  
302    (<https://ccp-odc.eva.mpg.de/tango-cc/manual.html>). (2) For adding a new language in the online  
303    version of the task, researchers can contact the first author of this paper. Please note that this  
304    option requires new audio recordings by the interested researchers, which will then be openly  
305    available for all users of the task. All written instructions in the task are solely for the research  
306    assistant to help them guide participants through the task; these instructions are solely available

307 in English. The task can either be started with the default settings or further customized by  
308 adapting the number of trials, agents, and background scenes. The default settings use the  
309 version applied in Bohn et al. (2024) based on the selected language (see Supplements).

310 If researchers choose to customize the task (see Figure 2), they can adjust the number of  
311 trials for each trial type, but not their sequence. Specifically, trial types build on each other and  
312 participants need to complete each trial type (without skipping any) to understand the structure  
313 of the task. The minimum number of trials per type is 1; the maximum is 100. Furthermore,  
314 researchers can customize backgrounds by selecting one of four different backgrounds. Finally,  
315 researchers can choose from 50 diverse cartoon-like human faces (50% female, 50% male) and  
316 freely select how many different faces to include (min 1, max 50). Once all the settings are  
317 selected, the customized task is compiled. To save the selected settings, researchers can  
318 bookmark the URL to easily access the customized task.

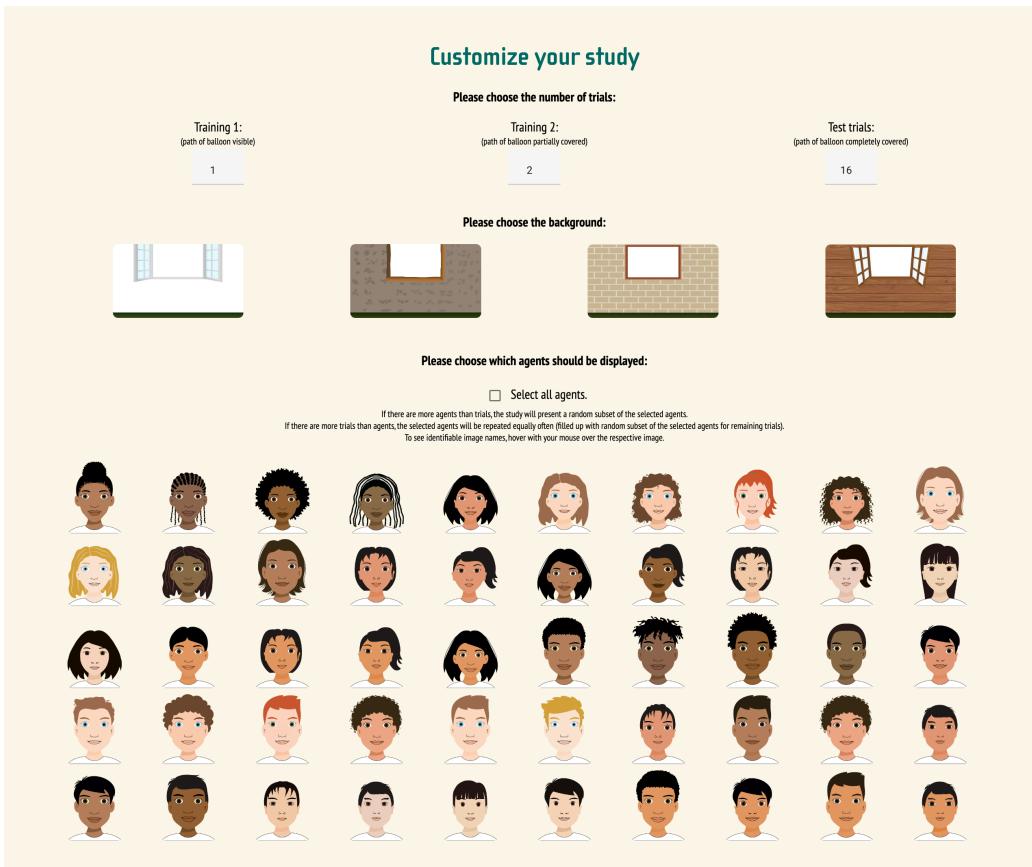
319 In the last step, researchers can enter an alphanumeric participant identifier (1 - 8  
320 characters) and enable a webcam recording of the participant, if needed. A webcam recording  
321 might prove especially helpful for unsupervised online data collection to ensure that the  
322 participant is alone during the task and no help is provided. The participant identifier and  
323 webcam choice have to be provided every time the task is run.

324 The source code of the task is openly available on GitHub  
325 (<https://github.com/ccp-eva/tango-cc>). By directly editing the HTML and JavaScript code,  
326 researchers can further modify the task as needed.

327 We created a public OSF page (<https://doi.org/10.17605/OSF.IO/P2EGU>) on which we  
328 plan to collect data sets that used the TANGO-CC. Researchers who have collected data using  
329 the TANGO-CC can share their data with the community by contacting the first author of this  
330 paper or visiting the OSF repository.

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**Figure 2**

**Screenshot of the customizable components of the TANGO-CC.** Researchers can select the language of the audio instructions (see Table 1), the number of trials per trial type, the background, and the agent's face.

**Table 1***Current language options available for the audio instructions in the TANGO-CC*

Languages	Language family	Speaker's country of origin
Bemba	Bantu	Zambia
Chinese	Sino-Tibetan	China
English	Indo-European	USA / UK / India / Nigeria / New Zealand
German	Indo-European	Germany
(#Akhoe) Hai  om	Khoe-Kwadi	Namibia
Khwedam	Khoe-Kwadi	Namibia
Lingala	Bantu	Rep. Congo
Marathi	Indo-European	India
Shona *	Bantu	Zimbabwe
Spanish	Indo-European	Argentina (Rioplatense Spanish) / Mexico (Mexiquense Spanish)
Kiswahili	Bantu	Uganda
Turkish	Turkic	Türkiye
Yaka	Bantu	Rep. Congo

*Note.* In cases where more than one speaker's country of origin is listed, the audio instructions were recorded multiple times by different speakers. For example, the English instructions are available in five different versions. \* Please note that audio instructions are available in Shona but no data of this version is included in the present data set.

<sup>331</sup> **Task implementation**

<sup>332</sup> The task was implemented in JavaScript, HTML, and CSS and is presented as a  
<sup>333</sup> web app. It can be accessed on any modern web browser on any device (e.g., computer or tablet)  
<sup>334</sup> and does not require prior installation (though please note that configurations of browsers and  
<sup>335</sup> JavaScript may change in the future). Participant's responses can be recorded on a touchscreen  
<sup>336</sup> or with a mouse or trackpad. The online version of the task can be used for unsupervised data  
<sup>337</sup> collection (for example, using online platforms like *Prolific*; see Prein et al. (2023)). The task can  
<sup>338</sup> be shared easily internationally by providing the URL. Importantly, the web app  
<sup>339</sup> implementation does not require a working WIFI connection: An offline version of the task can  
<sup>340</sup> be downloaded and quickly set up for devices that support Node.js (<https://nodejs.org/en>). This  
<sup>341</sup> is an especially useful feature for researchers working in locations with limited internet access.

<sup>342</sup> The stimuli are embedded as Scalable Vector Graphics (SVG; an image format that stores

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343 image elements via mathematical formulas based on points and lines on a grid). SVGs ensure  
344 that the picture quality, aspect ratio, and relative object positioning are constant. Furthermore,  
345 stimuli are added as individual components to the image scene which allows for an easy  
346 adaptation of the task's elements (in contrast to other image formats that consist of only one  
347 combined layer that would need entire replacement). The task is programmed so that responses  
348 are only registered when the participant clicks the relevant part of the screen (*i.e.*, in test trials,  
349 when they click the hedge). Furthermore, clicks are only registered after the voice recordings  
350 stop playing. An audio reminder is played again if no click is registered within 5 seconds.

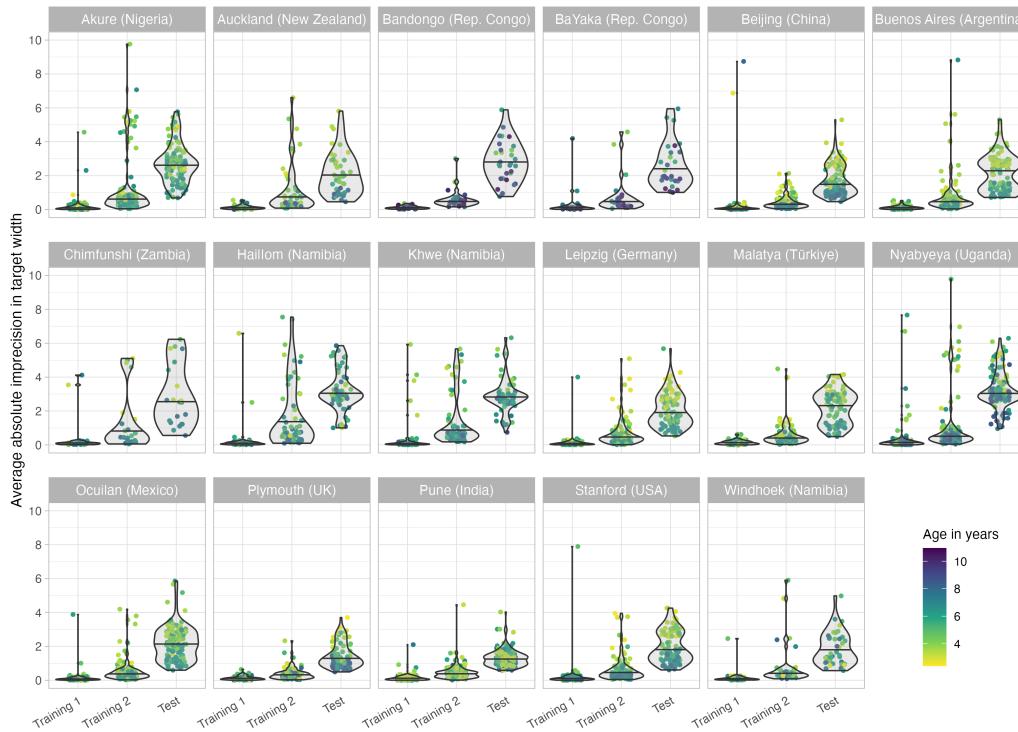
351 The website does not use cookies, nor does it upload any data to servers; that is, the data  
352 is only stored locally on the device. The output of the task is a CSV file (and WEBM file if a  
353 webcam recording was selected) that contains the participants' responses and can be easily  
354 imported into statistical software for further analysis. The file will be stored in the device's  
355 downloads folder and is named after the following pattern:  
356 “tangoCC-participantID-YYYY-MM-DD\_hh\_mm\_ss”. To modify the storage location on the  
357 device, researchers can change the designated downloads folder in their browser settings.

### 358 **Psychometric evaluation**

#### 359 **Data set**

360 We used the data set from Bohn et al. (2024) for the psychometric evaluation of the  
361 TANGO-CC. The data set contains a sample of  $N = 1377$  children, aged 2.5 to 11 years.  
362 Participants came from 17 communities on five continents, in rural and urban settings, with  
363 varying degrees of market integration and technology exposure. Bohn et al. (2024) carried out  
364 19 trials (1 training 1, 2 training 2, and 16 test trials, of which the first of each type had audio  
365 instructions) on a touchscreen device. Faces, backgrounds, and languages were chosen by  
366 researchers and assistants with experience in the specific community. For further details on the  
367 communities, participant information, and data collection procedures, see the supplements of  
368 Bohn et al. (2024).

<sup>369</sup> **Individual differences**



**Figure 3**

**Variability measured by the TANGO-CC.** Mean imprecision in locating the agent's attentional focus by community (alphabetically) and trial type. Imprecision is defined as the distance between the participant's click and the balloon's center in units of balloon width. For a depiction of each trial's procedure, see Figure 1.

<sup>370</sup> All analyses and the data set can be accessed on GitHub

<sup>371</sup> (<https://github.com/ccp-eva/tango-cc-methods/>). First, we inspected the mean and standard <sup>372</sup> deviations by community and compared performance in each trial type (training 1, training 2, <sup>373</sup> test trials). Performance was defined as the absolute distance between the target center and the <sup>374</sup> x coordinate of the participant's click (measured in balloon widths). Across communities, <sup>375</sup> children performed best in training 1 (mean = 0.19, sd = 0.63), followed by training 2 (mean = <sup>376</sup> 0.79, sd = 1.44) and test trials (mean = 2.21, sd = 2.03; see Figure 3).

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377 To formally estimate the effect of trial type on performance in the TANGO-CC, we  
378 fitted a generalized linear mixed model (GLMM) predicting the task performance by trial type  
379 (reference category: test trials). All analyses were run in R version 4.4.0 (2024-04-24) (R Core  
380 Team, 2024). GLMMs were fitted with default priors using the function `brm` from the package  
381 `brms` (Bürkner, 2017, 2018). The model included random effects for trial type by community  
382 (model notation in R: `imprecision ~ trialtypes + (triaitype |`  
383 `community)`), and imprecision was modeled by a lognormal distribution. We inspected  
384 the posterior distribution (mean and 95% Credible Interval (CrI)) for the trial type estimates.

385 Our GLMM analysis supported the visual inspection of the data: the fixed-effect  
386 estimates for training 1 ( $\beta = -3.26$ ; 95% CrI [-3.41; -3.10]) and training 2 ( $\beta = -1.47$ ; 95% CrI [-1.58;  
387 -1.35]) were negative and reliably different from zero.<sup>1</sup> This effect was found across all  
388 communities (random effects of trial type within community: minimum estimate for training 1  
389 = -2.87; 95% CrI [-3.11; -2.60]; minimum estimate for training 2 = -1.27; 95% CrI [-1.51; -0.98]). The  
390 almost perfect performance in training trials indicated that children understood the task and  
391 were able to correctly indicate the location of the balloon when its path was (mostly) visible. In  
392 test trials, children's imprecision was higher, indicating that the task was more challenging. All  
393 communities showed substantial individual variation and overlapped in their imprecision levels  
394 (see Figure 3).

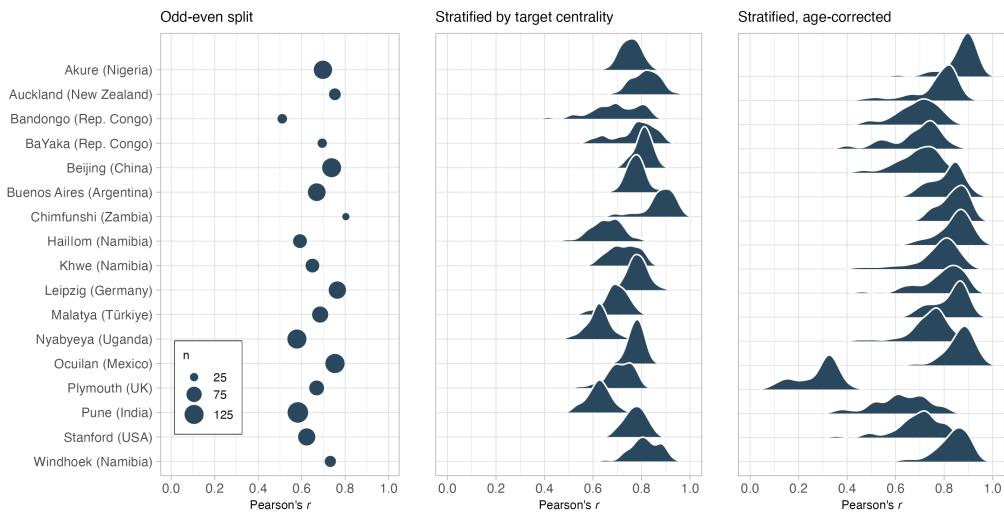
395 To identify the sources of variation, we computed intraclass correlations (ICC). The  
396 variation in children's imprecision within communities was substantially larger than the  
397 variation between the communities. The mean within-community variance was 1.28, ranging  
398 from 0.24 (in Pune, India) to 3.46 (in Chimfunshi, Zambia). Between-community variance was  
399 0.34. The ICC, representing the proportion of between-community variance relative to the total  
400 variance (sum of within- and between-community variance), was 0.02. This indicated that only

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<sup>1</sup> Please note that the TANGO-CC measures imprecision in gaze following. Therefore, a negative sign indicates that children showed less imprecision (*i.e.*, were more precise) in the training trials than in the test trials.

401 2% of the total variability in the data could be attributed to differences between communities,  
 402 while the remaining 98% were attributed to differences within communities (Kusano et al., 2024).

403 **Reliability**



**Figure 4**

**Reliability of the TANGO-CC by community.** Internal consistency estimates by community, following three different approaches. In the odd-even split, the size of points reflects the sample size in each community. In the stratified approach with and without age correction, density curves show the posterior distributions of the GLMM.

404 To assess reliability, we estimated internal consistency in each community in three  
 405 different ways. First, data of each participant was split into odd and even trials and a Pearson  
 406 correlation was calculated between the aggregated scores of the two halves. Second, using the  
 407 function `by_split` from the `splithalfr` package (Pronk et al., 2022), data was stratified  
 408 by target centrality (capturing trial difficulty), and a Pearson correlation was calculated between  
 409 the matched halves. Third, a data set was generated with stratified test halves by target  
 410 centrality and we applied the GLMM approach introduced by Rouder and Haaf (2019). A GLMM  
 411 was fitted with the mean imprecision as the outcome, age as the predictor, and test half and  
 412 participant id as random effects (model notation: `imprecision ~ age + (0 + half`  
 413 `| subj_id)`). The model estimates correlations between participant-specific estimates for

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414 each test half. The hierarchical shrinkage of the model enables accurate person-specific  
415 estimates. By incorporating age as a fixed effect, the correlation between the two  
416 person-specific estimates represents the age-independent estimate for internal consistency. This  
417 removes the possibility that a good internal consistency estimate results from general cognitive  
418 development rather than task-specific inter-individual differences. Because the process of  
419 generating stratified data sets is partly random, the model was fitted 50 times for each  
420 community. The posterior estimate of the correlation between the two person-specific estimates  
421 was taken as the age-independent estimate for internal consistency.

422 The results are shown in Figure 4. Across communities, internal consistency estimates  
423 ranged from 0.51 to 0.80 for the odd-even split, 0.62 to 0.89 for the stratified internal consistency,  
424 and 0.62 to 0.87 for the age-corrected approach (Plymouth, UK, being an outlier with 0.28).  
425 Following Cohen's suggestions (Cohen, 1988, 1992), these correlations constitute large effects ( $r$   
426  $> .50$ ), and indicate good internal consistency.<sup>2</sup> The results are comparable to the internal  
427 consistency estimates found in the original TANGO study (Prein et al., 2023), and also resemble  
428 reliability estimates of classical false belief tasks (Hughes et al., 2000).

429 In an exploratory analysis, we found that communities with larger individual variation  
430 showed higher internal consistency estimates (Pearson's  $r = 0.46$ , 95%CI [-0.03; 0.77]). This  
431 suggests that the less variation a task can capture within a community, the lower the reliability.  
432 However, please note that this correlation could be influenced by outliers and that the sample  
433 size here ( $N = 17$  communities) is too small to make substantial claims.

434 **Discussion**

435 The TANGO-CC measures imprecision in gaze following across individuals, ages, and  
436 communities. Children's imprecision in gaze following showed highly similar result patterns  
437 across communities: children performed better in the training than the test trials, and

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<sup>2</sup> Note that for scale reliability and Cronbach's  $\alpha$ , values of .7 to .8 have been suggested to be acceptable (Field et al., 2012; Kline, 1999). However, Kline (1999) suggested that values below .7 could be realistic for psychological constructs due to their variable nature.

438 within-community variation greatly exceeded between-community variation. Furthermore, the  
439 task showed satisfactory to high reliability across all communities. Therefore, the TANGO-CC  
440 is a suitable task to capture individual differences in social-cognitive development in diverse  
441 communities.

442 The TANGO-CC's design process lays out a much-needed pragmatic approach to  
443 studying community-level and individual-level differences across cultures: While we performed  
444 a detailed psychometric evaluation of the task in a German setting, we collaborated with local  
445 researchers for the cross-cultural stimulus development and selection. Importantly, we  
446 re-assessed the TANGO-CC's psychometric properties in a large and diverse data set. While we  
447 cannot generalize our findings to all communities worldwide, we found that the TANGO-CC  
448 captured reliable individual variation in all 17 communities studied by Bohn et al. (2024). We  
449 hope that not just the TANGO-CC but also our pragmatic approach to constructing it will be  
450 helpful to other researchers. We recommend that researchers consider generalizability concerns  
451 and cross-cultural applications of their tasks and collaborate with local researchers at the early  
452 stages of task development (Torréns et al., 2023). Using the TANGO-CC (or any other task) in a  
453 new community requires sensitivity to the specific context, piloting, and, most importantly, the  
454 involvement of researchers or research assistants from the specific community.

455 Bourdage et al. (2023) pointed out a major challenge with adapting social cognition tasks  
456 to diverse communities: the number of world cultures is vast, and communities are constantly  
457 changing. Therefore, a promising approach might be to provide tasks with a modular system  
458 where components can be modified (*i.e.*, building block structure). In the case of the  
459 TANGO-CC, the task cannot only be adapted to different languages, cartoon faces, and  
460 backgrounds (see Figure 2) but also updated with new stimuli. Unlike studies that present  
461 sequential, hand-painted pictures that are difficult to adapt (Mehta et al., 2011), the TANGO-CC  
462 uses SVGs (Scalable Vector Graphics) that can be easily exchanged.

463 Compared to one of the most commonly used social cognition measures – the

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464 change-of-location false belief task (Baron-Cohen et al., 1985; Wimmer & Perner, 1983) – the  
465 TANGO–CC has several advantages: a continuous outcome measure that can capture individual  
466 differences from three years to adulthood, a short task duration that allows for more trials per  
467 child, stimuli that can be easily adapted, and known psychometric properties across 17  
468 communities. The task is presented as a web app that enables efficient data collection with large  
469 sample sizes, while it can also be used to collect data offline in locations without a reliable  
470 internet connection. The TANGO–CC follows a standardized procedure, which leaves no room  
471 for rater errors and greatly simplifies online training of research assistants. Furthermore,  
472 minimal language demands and an engaging, playful design increase the task’s usability and  
473 reduce non-completion rates.

474 The TANGO–CC is a screen-based task. Bohn et al. (2024) have shown that children  
475 with no prior touchscreen exposure were less precise in the TANGO–CC than children with  
476 prior experience. However, individual differences were also found in communities with 100%  
477 touchscreen exposure, showing that this factor alone could not explain children’s performance  
478 in the task (Bohn et al., 2024). Notably, even though the touchscreen experience caused absolute  
479 differences in task performance, all communities showed the same processing signature. A  
480 recent computational cognitive model described gaze following as a process of estimating pupil  
481 angles and the corresponding gaze vectors (Prein et al., 2024). Bohn et al. (2024) found clear  
482 support for this model in every community studied, suggesting that children all over the world  
483 process gaze in a similar way. Nevertheless, the mode of stimulus presentation needs to be kept  
484 in mind when administering the TANGO–CC, especially in communities with little technology  
485 exposure. Additional touchscreen training (e.g., more trials of training 1) might prove helpful in  
486 these cases.

487 Schilbach et al. (2013) pointed out that witnessing social interactions as an observer  
488 undoubtedly differs from actively participating in social interactions. First evidence suggests  
489 that the TANGO–CC indeed taps into social cognition as utilized in real life: Prein et al. (2024)

490 found that children's perspective-taking abilities in a personal social interaction were linked to  
491 performance in the TANGO, but less so to a matched, non-social vector following task.  
492 However, this study exclusively relied on a German sample and future research should  
493 investigate whether the relationship between the TANGO-CC and perspective-taking abilities  
494 holds across communities.

495 We have reported reliability estimates for each community by calculating internal  
496 consistency. Ideally, we would have additionally evaluated the task's test-retest reliability in  
497 each community and checked for relationships with theoretically related constructs to assess  
498 validity. Unfortunately, this might not always be feasible in large-scale cross-cultural studies  
499 due to organizational and financial constraints. An example of assessing the TANGO's  
500 predictive validity is a study conducted in Leipzig, Germany, which used the TANGO to predict  
501 children's receptive vocabulary 6 months later (Prein et al., 2023). Future cross-cultural studies  
502 could investigate the TANGO-CC's predictive validity and its relationship to other  
503 social-cognitive abilities (e.g., Theory of Mind, language development) in diverse communities.

504 Measurement invariance (*i.e.*, measuring the same construct across different  
505 communities) is often seen as a requirement for a "fair" cross-cultural comparison: it is  
506 important that any group differences are not the result of the task unintentionally tapping into  
507 different underlying constructs. As Kusano et al. (2024) put it: "The research challenge is to  
508 achieve a balance between ensuring methodological "fairness" at the individual level while also  
509 recognizing and capturing genuine sociocultural variability" (p. 34). We argue that the  
510 TANGO-CC measures a fundamental social-cognitive ability that is likely similar across  
511 communities. Selcuk et al. (2023) pointed out that researchers should study both within- and  
512 between-culture variability in the development of social cognition since sometimes  
513 within-culture differences exceed between-culture differences. Indeed, we found that  
514 within-group variability was greater than between-group variability. While we believe that the  
515 TANGO-CC can be used to compare mean differences across communities, we would

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516 recommend using it to study individual differences within communities.

517 For years, researchers have called for more diverse sampling and culturally valid  
518 measures of cognitive development (Matsumoto & Yoo, 2006; e.g., Mehta et al., 2011; Nielsen et  
519 al., 2017). As Hajdúk et al. (2020) said, “using large samples and multisite approaches will align  
520 with efforts to improve reproducibility [replicability] and will clarify both the type and extent of  
521 cultural influences on social cognition” (p. 463). Similarly, Elson et al. (2023) have called for  
522 standardized, psychometrically evaluated measures that can be re-used by other researchers in  
523 order to “build a cumulative evidence base in psychology” (p. 2). This underlines how efforts to  
524 improve replicability can be combined with the goal of increasing the generalisability of  
525 psychological research findings (Li et al., 2024; Syed, 2021). Li et al. (2024) have argued that  
526 replicable and generalizable results rely on stimulus sets with slight variations, more diverse  
527 samples, and data collection at a greater scale, which are indeed all steps the TANGO-CC has  
528 taken. Openly sharing the TANGO-CC’s materials will allow other researchers to (hopefully)  
529 replicate the results and deepen our cumulative understanding of social-cognitive development  
530 across diverse communities.

531 **Conclusion**

532 The TANGO-CC captures individual differences in social-cognitive development across  
533 diverse communities. The task’s customizability, minimal language demands, and its efficient  
534 data collection method make it a valuable tool for cross-cultural research. The task showed  
535 satisfactory to high reliability (internal consistency) in a large data set including 17 diverse  
536 communities on five continents. We hope that the TANGO-CC – and its pragmatic construction  
537 process – will provide a roadmap for future cross-cultural studies on cognitive development.

538

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# Appendix B — Further Publications

The following Appendix B contains other publications of side projects that were written in the context of the dissertation but not included in the main text, with their respective abstracts.

## Action anticipation based on an agent's epistemic state in toddlers and adults

**Citation:** Schuwerk, T., Kampis, D., Baillargeon, R., Biro, S., Bohn, M., Byers-Heinlein, K., Dörrenberg, S., Fisher, C., Franchin, L., Fulcher, T., Garbisch, I., Geraci, A., Grosse Wiesmann, C., Hamlin, K., Haun, D. B. M., Hepach, R., Hunnius, S., Hyde, D. C., Karman, P., ..., Prein, J., ... Rakoczy, H. (2021). *Action anticipation based on an agent's epistemic state in toddlers and adults*. *Child Development* [In-Principle Acceptance of Registered Report Stage 1: Study Design]. PsyArXiv. <https://doi.org/10.31234/osf.io/x4jbm>

**Abstract:** Do toddlers and adults engage in spontaneous Theory of Mind (ToM)? Evidence from anticipatory looking (AL) studies suggests that they do. But a growing body of failed replication studies raised questions about the paradigm's suitability. In this multi-lab collaboration, we test the robustness of spontaneous ToM measures. We examine whether 18- to 27-month-olds' and adults' anticipatory looks distinguish between two basic forms of an agent's epistemic states: knowledge and ignorance. In toddlers [ANTICIPATED n = 520 50% FEMALE] and adults [ANTICIPATED n = 408, 50% FEMALE] from diverse ethnic backgrounds, we found [SUPPORT/NO SUPPORT] for epistemic state-based action anticipation. Future research can probe whether this conclusion extends to more complex kinds of epistemic states, such as true and false beliefs.

*Please note that this abstract was written for the Registered Report and does not entail results yet. Text in square brackets indicates placeholder text to be filled in after data collection.*

## **PREVIC: An adaptive parent report measure of expressive vocabulary in children between 3 and 8 years of age**

**Citation:** Bohn, M., Prein, J. C., Engicht, J., Haun, D., Gagarina, N., & Koch, T. (2023). *PREVIC: An adaptive parent report measure of expressive vocabulary in children between 3 and 8 years of age*. [Manuscript submitted for publication]. PsyArXiv. <https://doi.org/10.31234/osf.io/hvncp>

**Abstract:** Parent report measures have proven to be a valuable research tool to study early language development. Caregivers are given a list of words and are asked which of them their child has already used. However, most available measures are not suited for children beyond infancy, come with substantial licensing costs or lack a clear psychometric foundation. Here we present the PREVIC (Parent Report of Expressive Vocabulary in Children), an open access, high quality vocabulary checklist for German-speaking children between three and eight years of age. The PREVIC was constructed leveraging the advantages of Item Response Theory: we designed a large initial item pool of 379 words and collected data from  $N = 1190$  caregivers of children between three and eight years of age. Based on this data, we computed a range of fit indices for each item (word) and used an automated item selection algorithm to compile a final pool that contains items that a) vary in difficulty and b) fit the Rasch (one-parameter logistic) model. The resulting task is highly reliable and shows convergent validity. The IRT-based construction allowed us to design an adaptive version of the task, which substantially reduces the duration of the task while retaining measurement precision. The task – including the adaptive version – was implemented as a website and is freely accessible online (<https://ccp-odc.eva.mpg.de/previc-demo/>). The PREVIC fills an important gap in the toolkit of researchers interested in language development and provides an ideal starting point for the development of converging measures in other languages.

## **oREV: An item response theory-based open receptive vocabulary task for 3- to 8-year-old children**

**Citation:** Bohn, M.\*, Prein, J.\*, Koch, T., Bee, R. M., Delikaya, B., Haun, D., & Gagarina, N. (2024). oREV: An item response theory-based open receptive vocabulary task for 3- to 8-year-old children. *Behavior Research Methods*, 56(3), 2595–2605. <https://doi.org/10.3758/s13428-023-02169-3>

**Abstract:** Individual differences in early language abilities are an important predictor of later life outcomes. High-quality, easy-access measures of language abilities are rare, especially in the preschool and primary school years. The present study describes the construction of a new receptive vocabulary task for children between 3 and 8 years of age. The task was implemented as a browser-based web application, allowing for both in-person and remote data collection via the internet. Based on data from  $N = 581$  German-speaking children, we estimated the psychometric properties of each item in a larger initial item pool via item response modeling. We then applied an automated item selection procedure to select an optimal subset of items based on item difficulty and discrimination. The so-constructed task has 22 items and shows excellent psychometric properties with respect to reliability, stability, and convergent and discriminant validity. The construction, implementation, and item selection process described here makes it easy to extend the task or adapt it to different languages. All materials and code are freely accessible to interested researchers. The task can be used via the following website: <https://ccp-odc.eva.mpg.de/orev-demo>.

## **Validation of an open source, remote web-based eye-tracking method (WebGazer) for research in early childhood**

**Citation:** Steffan, A., Zimmer, L., Arias-Trejo, N., Bohn, M., Dal Ben, R., Flores-Coronado, M. A., Franchin, L., Garbisch, I., Grosse Wiesmann, C., Hamlin, J. K., Havron, N., Hay, J. F., Hermansen, T. K., Jakobsen, K. V., Kalinke, S., Ko, E.-S., Kulke, L., Mayor, J., Meristo, M., ..., Prein, J., ..., Schuwerk, T. (2024). Validation of an open source, remote web-based eye-tracking method (WebGazer) for research in early childhood. *Infancy*, 29(1), 31–55. <https://doi.org/10.1111/infa.12564>

**Abstract:** Measuring eye movements remotely via the participant’s webcam promises to be an attractive methodological addition to in-person eye-tracking in the lab. However, there is a lack of systematic research comparing remote web-based eye-tracking with in-lab eye-tracking in young children. We report a multi-lab study that compared these two measures in an anticipatory looking task with toddlers using WebGazer.js and jsPsych. Results of our remotely tested sample of 18-27-month-old toddlers ( $N = 125$ ) revealed that web-based eye-tracking successfully captured goal-based action predictions, although the proportion of the goal-directed anticipatory looking was lower compared to the in-lab sample ( $N = 70$ ). As expected, attrition rate was substantially higher in the web-based (42%) than the in-lab sample (10%). Excluding trials based on visual inspection of the match of time-locked gaze coordinates and the participant’s webcam video overlayed on the stimuli was an important preprocessing step to reduce noise in the data. We discuss the use of this remote web-based method in comparison with other current methodological innovations. Our study demonstrates that remote web-based eye-tracking can be a useful tool for testing toddlers, facilitating recruitment of larger and more diverse samples; a caveat to consider is the larger drop-out rate.

# Appendix C — Social Cognition Survey

In Autumn/Winter 2020, we conducted a short online expert survey on defining social cognition, as reported in the Introduction. Below you find the full survey, including the questions and the answers of the experts.

**E-Mail that we sent out:**

Dear all,

At the Max Planck Institute for Evolutionary Anthropology, we are planning to design a test battery that reliably measures individual differences in social cognition in children between 2 and 5 years of age. As a first step in this process, we are reaching out to the community of developmental psychologists. Your input will help us to decide on which aspects of social cognition to focus on.

We designed a short (5-minutes) survey and we would very much appreciate your input. Here's the link: [https://www.soscisurvey.de/soc\\_cog/](https://www.soscisurvey.de/soc_cog/) [PLEASE NOTE: LINK IS NOT ACTIVE ANYMORE]

In addition to the survey, we are searching the literature for studies that looked at individual differences in children's social cognition. This will point us to the established tasks that "work" (i.e., produce meaningful variation).

Thank you very much for your time. If you have any feedback, we would be very happy to receive it.

Best,

Julia Prein, Manuel Bohn and Daniel Haun

**Data collection period:** November – December 2020

## *Appendix A — Overview of Articles Included in the Dissertation*

### **Screenshots of the online survey:**

Page 1:

The screenshot shows the start of an online survey. At the top right is the institute's logo, which is a circular emblem featuring a profile of a head with a laurel wreath. The main title "MAX PLANCK INSTITUTE" is in large, bold, teal capital letters, followed by "FOR EVOLUTIONARY ANTHROPOLOGY" in smaller capital letters. Below the title is a horizontal line. Underneath the line, the text reads: "Thank you for your interest in our survey on ‘Defining Social Cognition’." It continues with a paragraph about the survey's goal, risks, and voluntary participation. It also mentions the survey was conducted by Julia Prein, Manuel Bohn, and Daniel Haun from the Max Planck Institute for Evolutionary Anthropology, Leipzig, Germany. It provides contact information and a link to the imprint. Below this text is a consent form with two radio button options: "No, I do not agree (do not participate in this survey)." and "Yes, I agree (participate in this survey)." To the right of the "Yes" option is a "Next" button. At the bottom left is the name "Julia Prein, Max Planck Institute for Evolutionary Anthropology – 2020". To the right is a progress bar indicating "0% completed".

Page 2:

The screenshot shows the second page of the survey. The Max Planck Institute logo is at the top right. The main title "MAX PLANCK INSTITUTE" is in large, bold, teal capital letters, followed by "FOR EVOLUTIONARY ANTHROPOLOGY" in smaller capital letters. Below the title is a horizontal line. Underneath the line, the text reads: "Welcome to our online survey!" It explains that Social Cognition is often used as an umbrella term to refer to a wide range of cognitive processes and abilities. The survey focuses on Social Cognition from a developmental and individual differences perspective. It will ask questions about how people define Social Cognition as a psychological construct and ask for opinions on aspects of Social Cognition. It also states that the survey aims to inform the design of new tasks to measure individual differences in Social Cognition in children. Your expert opinion will help select the most important aspects of Social Cognition to focus on. Below this text is a "Next" button. At the bottom left is the name "Julia Prein, Max Planck Institute for Evolutionary Anthropology – 2020". To the right is a progress bar indicating "14% completed".

Page 3:

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We searched the literature for definitions of Social Cognition. Below you can find a (non-exhaustive) list.\*  
Which definition do you most agree with?

Social cognition...

is the process by which actors, at individual or collective levels, decode and encode their social world, using mental models, knowledge structures and cultural understandings to process information, extract meaning and determine appropriate action [1]

is the ability to attribute mental states to oneself and others [2]

is the sum of those processes that allow individuals of the same species (conspecifics) to interact with one another [3]

encompasses all the information-processing mechanisms that underlie how people capture, process, store, and apply information about others to navigate social situations [4]

concerns the various psychological processes that enable individuals to take advantage of being part of a social group [5]

is the ability to construct representations of the relations between oneself and others, and to use those representations flexibly to guide social behavior [6]

concerns learning about what matters in the social world [7]

is concerned with the study of the thought processes, both implicit and explicit, through which humans attain understanding of self, others, and their environment [8]

can be constructed as the process by which individuals develop the ability to monitor, control, and predict the behavior of others [9]

refers to the skills we use to think about others and ourselves in psychological terms [10]

other:

\* You can find the references for these definitions on the last page of the survey.

[Next](#)

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Julia Prein, Max Planck Institute for Evolutionary Anthropology – 2020 29% completed

Page 4:

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Social Cognition is a multi-faceted construct with many dimensions. Here is a (non-exhaustive) list of the dimensions that reoccurred in our literature search. Please note that we do not want to focus on the areas in which you can use Social Cognition. Rather, we are interested in what Social Cognition is (i.e., which different psychological subprocesses make up Social Cognition).

Please think about situations in which you discuss or write about Social Cognition. Which dimensions do you mention most often (choose five)?

beliefs

knowledge

emotions

goals

desires

reasoning

perspective-taking

attention

pretense

intentions

Please enter what you think is missing

Please enter what you think is missing

Please enter what you think is missing

**Next**

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43% completed

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We are primarily interested in individual differences in the development of Social Cognition. After an extensive literature review, we created the following list of aspects of Social Cognition.  
Which aspects would you expect children of the same age to vary?

The left side of the scale means that the presented item would not vary at all, while the right side of the scale means that the aspects would vary a lot between individuals. You are free to skip any item for which you don't have a strong opinion.

Children of the same age vary in how likely they are to...

	little variation	lots of variation
take another's perspective	○ ○ ○ ○ ○ ○	█ █ █ █ █ █
understand the subjectivity of knowledge states	○ ○ ○ ○ ○ ○	○ ○ ○ ○ ○ ○
learn from others	○ ○ ○ ○ ○ ○	○ ○ ○ ○ ○ ○
manipulate emotions	○ ○ ○ ○ ○ ○	○ ○ ○ ○ ○ ○
understand intentions	○ ○ ○ ○ ○ ○	○ ○ ○ ○ ○ ○
distinguish goal-directed from non-purposeful behavior	○ ○ ○ ○ ○ ○	○ ○ ○ ○ ○ ○
direct attention	○ ○ ○ ○ ○ ○	○ ○ ○ ○ ○ ○
recognise others as agents	○ ○ ○ ○ ○ ○	○ ○ ○ ○ ○ ○
play pretense	○ ○ ○ ○ ○ ○	○ ○ ○ ○ ○ ○
deceive others	○ ○ ○ ○ ○ ○	○ ○ ○ ○ ○ ○
simulate others' reasoning processes	○ ○ ○ ○ ○ ○	○ ○ ○ ○ ○ ○
attribute beliefs to others	○ ○ ○ ○ ○ ○	○ ○ ○ ○ ○ ○
remember one's own previous knowledge states	○ ○ ○ ○ ○ ○	○ ○ ○ ○ ○ ○
read facial expressions	○ ○ ○ ○ ○ ○	○ ○ ○ ○ ○ ○
recognise goals	○ ○ ○ ○ ○ ○	○ ○ ○ ○ ○ ○
follow gaze	○ ○ ○ ○ ○ ○	○ ○ ○ ○ ○ ○
understand diverse desires	○ ○ ○ ○ ○ ○	○ ○ ○ ○ ○ ○
share attention	○ ○ ○ ○ ○ ○	○ ○ ○ ○ ○ ○
recognise emotions	○ ○ ○ ○ ○ ○	○ ○ ○ ○ ○ ○
attribute knowledge and ignorance	○ ○ ○ ○ ○ ○	○ ○ ○ ○ ○ ○
imitate actions	○ ○ ○ ○ ○ ○	○ ○ ○ ○ ○ ○

Did we miss something? Can you think of other aspects of Social Cognition that are likely to vary between children of the same age? Please enter them below.  
If you have a reference in mind for the aspect(s) that we missed, we would love to have it. Thank you!

[Next](#)

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57% completed

Page 6:

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If you have any comments, thoughts or suggestions, we would love to hear them!

[Next](#)

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Page 7:

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Finally, we would like to ask for some personal information. Answering these questions is voluntary.

You are a ...	[Please choose]
You work in ...	[Please choose]
Do you conduct studies with children?	[Please choose]

You currently live in the following country ...

If you feel comfortable, you can tell us your name.\*

\* This will allow us to link your responses to your name. We would like to have your name to read up on your views. Your name will be kept strictly confidential and will not be published in any form.

[Next](#)

Julia Prein, Max Planck Institute for Evolutionary Anthropology – 2020      86% completed

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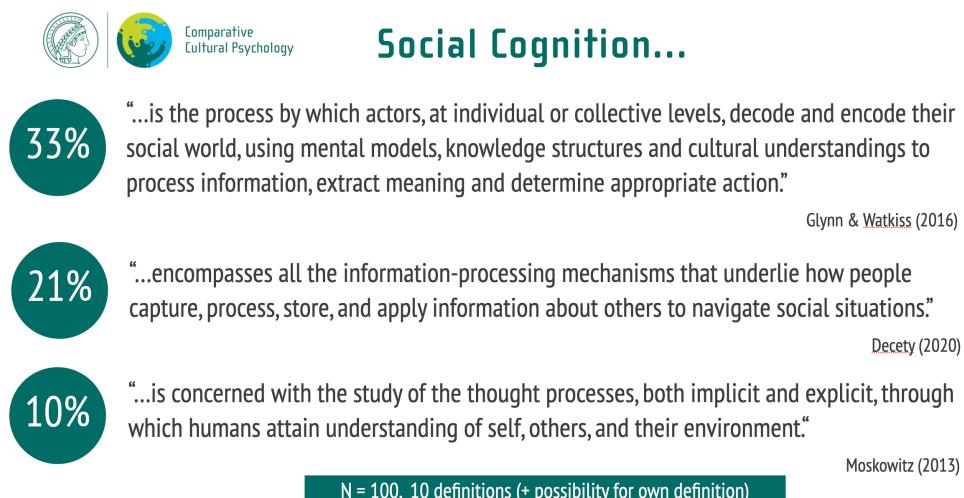
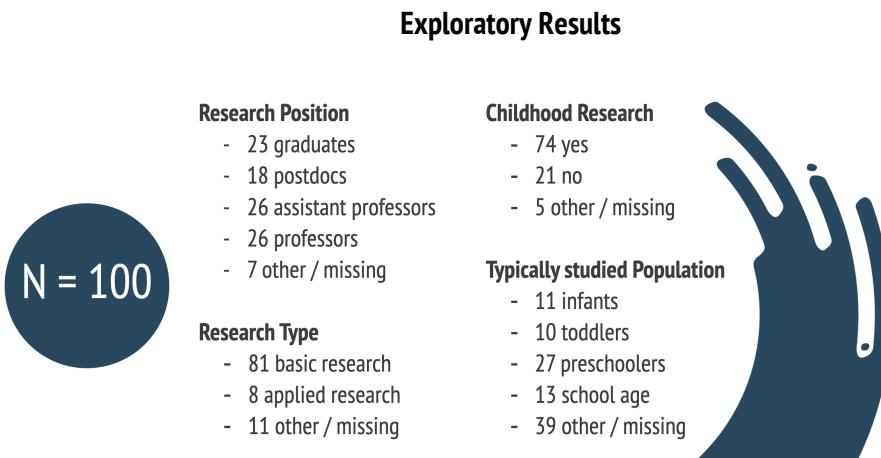
### Thank you for completing this questionnaire!

Your answers were transmitted, you may close the browser window or tab now.

In our first question of the survey, we listed some definitions of social cognition. Here is the list of references.

- [1] is the process by which actors, at individual or collective levels, decode and encode their social world, using mental models, knowledge structures and cultural understandings to process information, extract meaning and determine appropriate action. Glynn, M.A., & Watkiss, L. (2016). Social cognition. In M. Augier, D. Teece (Eds.), *The Palgrave Encyclopedia of Strategic Management*. Palgrave Macmillan, London. [https://doi.org/10.1057/978-1-349-94848-2\\_614-1](https://doi.org/10.1057/978-1-349-94848-2_614-1)
- [2] is the ability to attribute mental states to oneself and others. Dzibek, I., Fleck, S., Kalbe, E., Rogers, K., Hassenstab, J., Brand, M., . . . & Convit, A. (2006). Introducing MASC: A movie for the assessment of social cognition. *Journal of Autism and Developmental Disorders*, 36, 623–636. <https://doi.org/10.1007/s10803-006-0107-0>
- [3] is the sum of those processes that allow individuals of the same species (conspecifics) to interact with one another. Frith, C. D., & Frith, U. (2007). Social cognition in humans. *Current Biology*, 17 (16), R724–R732. <https://doi.org/10.1016/j.cub.2007.05.068>
- [4] encompasses all the information-processing mechanisms that underlie how people capture, process, store, and apply information about others to navigate social situations. Decety, J. (Ed.). (2020). *The Social Brain: A Developmental Perspective*. MIT Press.
- [5] concerns the various psychological processes that enable individuals to take advantage of being part of a social group. Frith, C. D. (2008). Social cognition. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, 363(1499), 2033–2039. <https://doi.org/10.1098/rstb.2008.0005>
- [6] is the ability to construct representations of the relations between oneself and others, and to use those representations flexibly to guide social behavior. Adolphs, R. (2001). The neurobiology of social cognition. *Current Opinion in Neurobiology*, (11), 231–239. [https://doi.org/10.1016/S0959-4388\(00\)00202-6](https://doi.org/10.1016/S0959-4388(00)00202-6)
- [7] concerns learning about what matters in the social world. Higgins, E. T. (2000). Social cognition: Learning about what matters in the social world. *European Journal of Social Psychology*, 30 (1), 3–39. [https://doi.org/10.1002/\(SICI\)1099-0992\(200001/02\)30:1::AID-EJSP987>3.0.CO;2-1](https://doi.org/10.1002/(SICI)1099-0992(200001/02)30:1::AID-EJSP987>3.0.CO;2-1)
- [8] is concerned with the study of the thought processes, both implicit and explicit, through which humans attain understanding of self, others, and their environment. Moskowitz, G.B. (2013). Social Cognition. *obo in Psychology*. <https://doi.org/10.1093/obo/9780199828340-0099>
- [9] can be constructed as the process by which individuals develop the ability to monitor, control, and predict the behavior of others. Rochat, P. and Striano, T. (1999). Social cognitive development in the first year. In Rochat, P. (Ed.), *Early Social Cognition: Understanding others in the first months of life*, pp. 3–34, Lawrence Erlbaum Associates Publishers.
- [10] refers to the skills we use to think about others and ourselves in psychological terms. Lewis, C., & Carpendale, J. (2014). Social cognition. In P. K. Smith & C. H. Hart (Eds.), *Wiley Blackwell handbooks of developmental psychology. The Wiley Blackwell handbook of childhood social development* (p. 531–548). Wiley Blackwell

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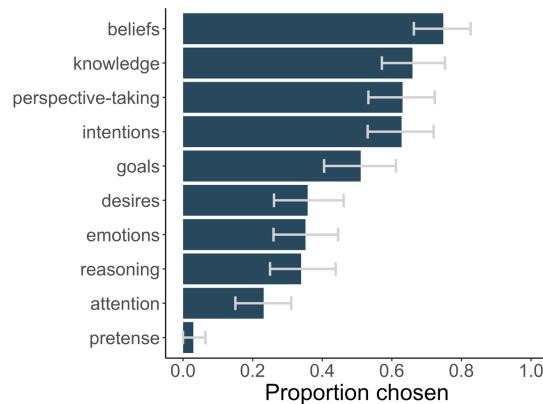


## Participants' own definitions of Social Cognition

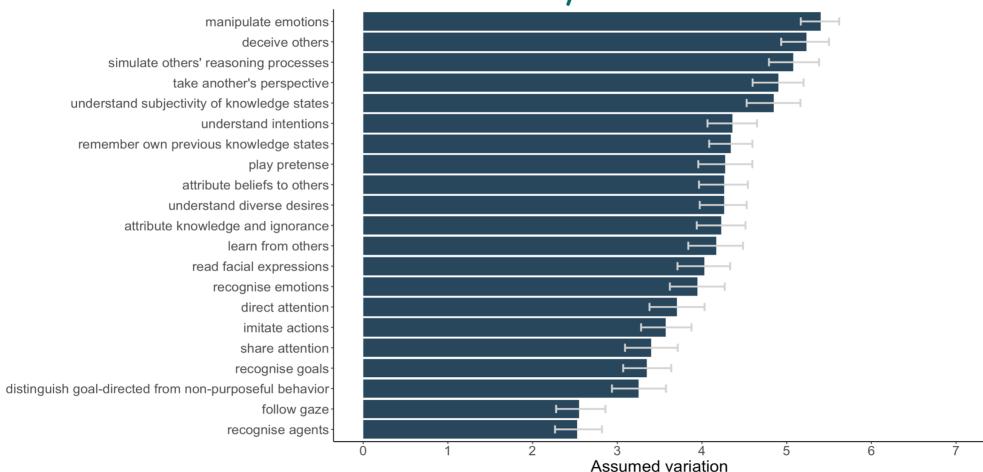
- “Cognition about social matters ranging from individuals (others and one self) and their subjective perspectives, feelings, etc. via groups to institutions”
- “Is the set of computations and representations specifically devoted to deal with conspecifics and their interactions”
- “Social cognition is the process by which we adopt or recognise a shared or non-shared perspective with other people”



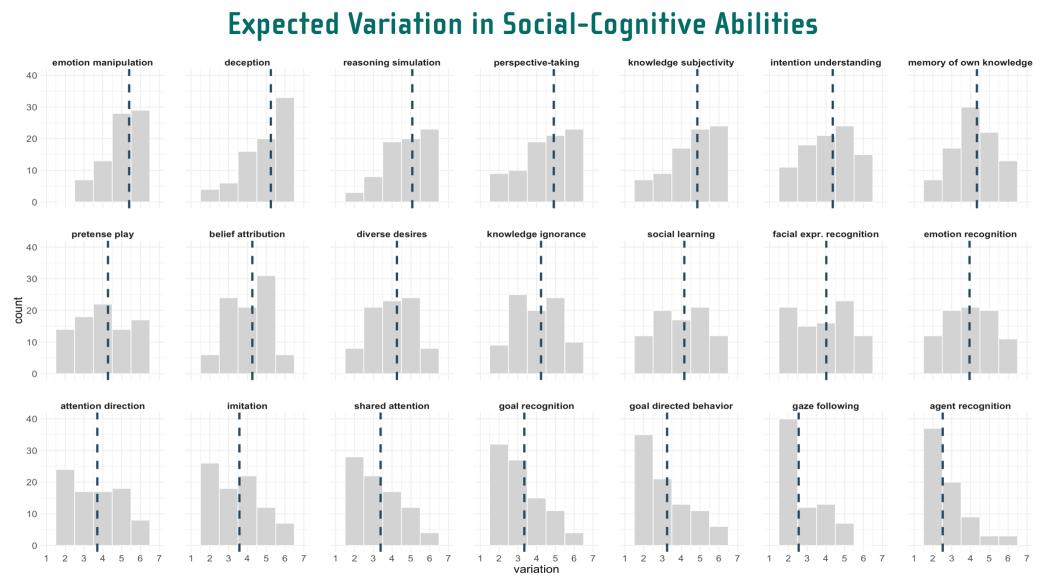
Please think about situations in which you discuss or write about Social Cognition. Which dimensions do you mention most often (choose five)?



Children of the same age vary in how likely they are to...



*Appendix A — Overview of Articles Included in the Dissertation*



# Acknowledgments

This dissertation rests on the shoulders of many inspiring, thought-provoking, motivating, and caring individuals. The last four years have been many different things – but definitely neither boring nor stagnant. I want to thank everyone who has accompanied me on this journey.

My motivation to work on this dissertation is greatly due to my wonderful supervisors. Manuel, I cannot thank you enough for supporting me. You have taught me to critically challenge the status quo in research and to focus my energy on improving it – pragmatically, step by step. Even though I do know that you believe there \*are\* stupid questions, I felt very comfortable to ask you all along the way and I have benefited a lot from your patience with me. Thanks for roughly 250 meetings that have always left me more motivated and focused than I was before. Daniel, I am so happy and proud to have been a member of the CCP team. Thank you for offering me so many unique opportunities and unforgettable memories, like traveling to conferences and Uganda. I am deeply impressed by how quickly you get a grasp of a new project and know immediately which questions to ask. Thank you for being such an approachable director and having an open door to hear about my personal struggles and to have philosophical discussions. To my external supervisor, Robert: your teaching in Research Methods has turned my hate for statistics into a deep passion. Thanks for encouraging me to do a PhD, for looking into open positions, and accompanying me along the way.

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I am grateful to our wonderful cohort of PhDs at the MPI. You are a remarkable group of people, and I am very happy that we could share our daily struggles with each other. Noemi, I am so glad that we got to share our office for a (way too short) period of time and successfully solved the Christmas murder mystery with Marie. Without my work wife Marie, my time during this dissertation would not have been even half as great as it has been. You have made me laugh so much, even if all I wanted to do was cry. Whatever it is that I am up to, I know you will always have my back and help me get back on my feet if I fail. I love your honesty, creativity, immense courage, charming awkwardness, and quirky sense of humor, and feel so honored that you are my friend. Thank you for being you!

## *Acknowledgments*

My dear, dear family, I am so deeply grateful to know you by my side. Whenever I talk about individual differences, I think about you, Caro, and how we two sisters have the same parents and yet are so different (in the very best way!!). I believe it is rare that siblings do not feel the need to compete with each other but can just love each other as they are. Thank you! To my mom, who told me right in the beginning that this journey would be a marathon and not a sprint. In some of my darker moments, you told me that even if it felt like I was about to fall, I could never – because there are so many caring people who would catch me beforehand. Thank you for always having an open home and lots of support (in the form of love, food, vacations, phone calls, and advice) for me. To my dad, thanks for showing up to Leipzig so often and establishing a little concert routine together! I believe I have learned a lot of my problem-solving skills and patience from you. Even if you do not remember saying "Mach Dinge richtig" in Caro's and my childhood, I think my dissertation has greatly benefited from this sentence. Thank you, Louis, for helping with my move to Leipzig and spontaneously catching up over coffee in Leipzig or Berlin. To my grandpa, who told me he never worried that I would find my own way. And to my grandma, for all your curiosity, play, and love for children. To the whole Gerken-Prein clan (including our furry friends) – I could not wish for a better family. Finally, we are reunited in the North.

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# Declaration of Independence

Julia Christin Prein

[Straße Hausnummer]

[PLZ Ort]

[Telefon]

[Email]

I hereby declare that I have not yet taken a doctoral examination or applied for admission to one.

I certify that the dissertation *Rethinking Variation in Social Cognition: Gaze Following across Individuals, Ages, and Communities* has not been submitted to any other university for review in the present or any other version.

I declare in lieu of oath that I have written the submitted dissertation *Rethinking Variation in Social Cognition: Gaze Following across Individuals, Ages, and Communities* independently and without any unauthorized outside help. I have not made use of any aids or writings other than those specified by me. I have labelled all passages taken literally or analogously from other writings. I have been informed of the consequences under criminal law in accordance with Art. 156 of the German Criminal Code.

Hamburg, [Datum]

[Unterschrift]