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

**Abstract**

Observing 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 - on a group level - has been thoroughly studied, we know little about (a) the developmental trajectory beyond infancy and (b) the sources of individual differences. In Study 1, we examined gaze understanding across the lifespan (*N* = 471 3- to 80-years-olds; children from a mid-sized German city; international remotely tested adults). We found a steep learning curve during preschool years, in which children become 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 understanding 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 tested two implications of our gaze model, namely that gaze understanding should be related to perspective-taking abilities and vector estimation in non-social settings (*N* = 102 4- to 5-year-olds). We found that gaze understanding 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:* social-cognitive development, theory of mind, gaze cues, individual differences, cognitive modeling, lifespan

*Word count:* xxx max 8000

**Research highlights**

* Gaze understanding develops beyond infancy. Highest precision levels in localizing attentional foci are reached in young adulthood with a slight decrease towards old age.
* We present a computational model as a mechanistic description of gaze understanding. The model explains individual differences and recovers signature patterns in the data.
* Our model assumes that gaze understanding relies on vector estimation. To test this assumption experimentally, we designed a non-social vector estimation task.
* We found substantial correlations between gaze understanding and vector estimation, as well as Level 2 perspective-taking. Other Theory of Mind tasks did not correlate.

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

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**Data availability 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 analysed during the current study are available in the [gazecues-modeling] repository (<https://github.com/ccp-eva/gazecues-modeling>). All experiments were pre-registered (<https://osf.io/zjhsc/>).

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# Introduction

How do humans learn about their environment and navigate their social surroundings? A promising approach to extract information from the environment is through following the gaze of others. Another’s eye gaze can guide us to “informational hotspots” (Meltzoff, Brooks, Shon, & Rao, 2010, p. 1) and proves helpful when learning about external objects or surroundings. Additionally, eye gaze can be used to identify internal states such as intentions or emotions (Corkum & Moore, 1998; Pfeiffer, Vogeley, & Schilbach, 2013), and is an integral part of almost every form of social interaction, including communication, collaboration, cultural and social learning (Bohn & Frank, 2019; Brooks & Meltzoff, 2005; Byers-Heinlein et al., 2021; Del Bianco, Falck-Ytter, Thorup, & Gredebäck, 2019; Emery, 2000; Meltzoff et al., 2010; Moore, 2008; Okumura, Kanakogi, Kobayashi, & Itakura, 2017; Senju & Csibra, 2008; Stephenson, Edwards, & Bayliss, 2021; Tomasello, Hare, Lehmann, & Call, 2007).

Existing studies operationalize gaze following as the ability to follow another agent’s line of sight. As one of the most fundamental social-cognitive abilities, it has been extensively studied in infancy (for review, see Del Bianco et al., 2019). The traditional, often-used paradigm to study gaze following looks as follows (e.g., Astor et al., 2020; Byers-Heinlein et al., 2021; Gredebäck, Fikke, & Melinder, 2010; Ishikawa, Senju, Kato, & Itakura, n.d.): The experimenter sits in front of the infant, with one object to their left and one to the right. The experimenter looks directly at the infant before shifting their head and eyes to one of the two objects. Infants’ looking times to the potential targets or choices of objects are recorded as dependent variables. Analyses traditionally focus on the average age at which children - as a group - reach an above-chance performance (i.e., looking at the gaze-cued target object). Research in this tradition finds that infants as young as six months can follow their gaze to that of another agent (D’Entremont, Hains, & Muir, 1997). 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, Flom, & Pick, 2000; Moll & Tomasello, 2004).

At first glance, the debate about children’s gaze following abilities seems to be settled: at 12 months of age, children are already competent gaze followers. On further view, however, some methodological choices in the experimental paradigms as well as the scope of infants’ abilities seem to offer room for further exploration. We see the following challenges: (1) Studies focus on infancy, leaving aside further development in childhood, adolescence and adulthood; (2) Gaze cues are often accompanied by head movements in the same direction (see Del Bianco et al., 2019), which makes it hard to isolate the referential information extracted from the eyes; (3) Infants’ looking times are usually used as the dependent variable and it is unclear if and how this would translate into active behavior; (4) Presenting two objects drastically limits the complexity of the visual input, especially when compared to our daily, visually cluttered environment; (5) Analyses focus on group-level averages, and we overlook variation in the sample because we cannot measure it with dichotomous outcome variables. In the following paragraphs, we will turn to each of these arguments and note how we addressed them consequently in our study.

First, while the emergence of gaze following has been well established, less is known about the developmental trajectory beyond infancy. One possibility is that the ability to follow gaze does not improve further once it emerges. Yet, most - if not all - cognitive abilities develop throughout childhood (e.g., working memory, Gathercole, Pickering, Ambridge, & Wearing, 2004). Similarly, visual processing appears to improve with age. First longitudinal evidence points to a development in the infant’s individual joint attention accuracy and latency (Gredebäck et al., 2010). It seems likely that children fine-tune the performance of the already existing skills - presumably while using them in social interactions. To capture further development in gaze understanding, we therefore conducted our Study 1 across the lifespan.

Second, we see in traditional gaze following studies that the experimenter often shifts their eyes and head in synchrony (e.g., Behne, Carpenter, & Tomasello, 2005; Okumura et al., 2017) so that children’s gaze following could be interpreted as following face direction alone. A handful of studies approached this potential confound by separately manipulating head and eye movement. Michel, Kayhan, Pauen, and Hoehl (2021) found that gaze following in four-month-olds was likely driven by another’s head instead of their eye movement. Brooks and Meltzoff (2002) implemented a comparison between eye and head orientation and found that 14-month-olds were sensitive to open versus closed eyes (see also Moore, Angelopoulos, & Bennett, 1997). Results of Corkum and Moore (1995), Lempers (1979), and Lempers, Flavell, and Flavell (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 can indicate a more precise location of focus (Emery, 2000), and allows us to anticipate likely future actions (Friesen & Rao, 2011; Zohary et al., 2022). Clearly, it is important to differentiate between head and gaze following. In our three studies, we focused on subtle gaze cues and isolated eye movement alone.

Third, let us consider the classical response measure of collecting looking times. Though previous studies suggest that young infants can align their visual attention to another’s line of sight, it does not necessarily include understanding the intentions or the focus of the agent (cf. Aslin, 2007). Infants could simply align their orientation without processing what exactly the other is seeing (cf. Butterworth & Jarrett’s ecological and geometric mechanism, Butterworth & Jarrett, 1991). In fact, one might ask if such an alignment reflects understanding of visual perspectives at all, because the “target” or “object of representation” is not necessarily specified (Perner, Brandl, Garnham, & Peter Lang, 2003, p. 358). To fulfill this criterion, Moll and Tomasello (2006) used an active behavioral choice as a response measure. Participants had to search for the target object, which was either visually accessible or behind a barrier. 24-month-olds succeeded in the task, while 18-month-olds did not. In an object choice study with two containers, Behne et al. (2005) found that already 14-month-olds used an experimenter’s gaze; however, this was again confounded with a congruent face movement (cf. Povinelli, Reaux, Bierschwale, Allain, & Simon, 1997). In this paper, we assessed how subtle gaze cues guided participants’ behavior in actively locating a target.

Finally, presenting two objects and focusing on group-level analyses masks individual differences between children in their gaze following abilities. Measuring individual differences in basic aspects of social cognition is especially 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). In our studies, we measured participants’ gaze understanding continuously by using a task which has been designed to capture individual-level variation (Prein, Kalinke, Haun, & Bohn, 2023).

## The current study

The present study had two main goals: first, we studied the development of gaze understanding beyond infancy on a group level (Study 1). Instead of capturing the youngest age at which children can follow gaze, we wanted to examine how this ability changes with age. Even though we found expected developmental patterns - rapid improvement in early childhood; some decline toward old age - we observed substantial variation between individuals at all ages. Our second goal was to provide a substantive process-level theory of gaze understanding (and individual differences therein) in the form of a computational model. We formalized gaze understanding as a form of vector estimation and showed that our model explained empirical data (Study 2). Furthermore, we tested two empirical predictions that followed from the model, namely that gaze understanding is related to non-social vector estimation and visual perspective-taking (Study 3).

# Study 1: Gaze understanding across the lifespan

We aimed to assess the developmental trajectory of gaze understanding across the lifespan. The study was pre-registered at: <https://osf.io/snju6> (child sample) and <https://osf.io/6yjz3> (adult sample). The study obtained ethical clearance by the MPG Ethics commission Munich, Germany, falling under an umbrella ethics application (Appl. No. 2021\_45), and was approved by an internal ethics committee at the Max Planck Institute for Evolutionary Anthropology. The research adhered to the legal requirements of psychological research with children in Germany. Data was collected between May 2021 and April 2023.

## Participants

We collected data online from participants between 3 to 80 years of age (see Supplements for further details). The child and teenager sample consisted of 471 participants and were recruited via an internal database consisting of families living in Leipzig, Germany, who volunteered to participate in child development studies and indicated an interest in online 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 (∼600,000 inhabitants; median individual monthly net income approx. 1,600€ 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 service from the University of Oxford with a predominantly European and US-American subject pool. Participants consisted of 240 English-speaking adults who reported to have normal or corrected-to-normal vision. For completing the study, subjects were paid above the fixed minimum wage (on average £10.00 per hour).

## Materials

We used the continuous version of the TANGO (Prein et al., 2023). The task was presented as an interactive web application (live demo [https://ccp-odc.eva.mpg.de/tango-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 for both children and adults (with reliability estimates *Pearson’s r* ranging from .7 to .8 for the continuous task version; (Prein et al., 2023)).

## Procedure

Children and teenagers received a personalized link to the study website. Caregivers were asked to provide technical support whenever needed, while explicitly being reminded not to help their children 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, please note that Study 1 presented animal agents). The target fell behind a hedge while the agent’s gaze followed the target’s trajectory: pupil and iris moved so that their center aligned with the target center. In test trials, the target flight was covered so that participants could not see where the target landed. Participants were tasked to locate the target by tracking the agent’s gaze. They could respond by touching or clicking the screen.

Four familiarization trials ensured that participants understood the task and felt comfortable with the response format. Then, 15 test trials followed. Completing the 19 trials took approximately 5-10 minutes.

The outcome measure was imprecision, defined as the absolute difference between the target (i.e., balloon) center and the x coordinate of the participant’s click. The full screen width was divided into ten bins. Within each bin, exact target coordinates were randomly generated during runtime. Each target bin, as well as all agents and target colors, occurred equally often and did not appear in more than two consecutive trials.

## Analysis

We ran all analyses in R version 4.3.1 (2023-06-16) (R Core Team, 2022). Regression models were fit 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 effect of age on gaze understanding, we fit GLMMs that make different assumptions about the developmental trajectory, modeling the relationship as linear, quadratic, or cubic. In addition, we applied a Gaussian Process model (Bürkner, 2017) and examined nonlinearity. The models predicted imprecision by age (continuous), aggregated across trials and modeled as a lognormal distribution.[[1]](#footnote-1) The unit of imprecision was counted in widths, i.e., a participant with an imprecision of 1 clicked on average 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, Gelman, & Gabry, 2017).

After finding that the developmental change was best described by the Gaussian process model, we performed a Bayesian change point analysis, using the package RBeast (Zhao et al., 2019). The function beast.irreg handled the irregular nature of our series, which did not have the same number of data points for each year in age. We were interested in finding the most prominent, most likely change points in our data, assuming a constant mean (i.e., a flat line, zero degree polynomial) within each segment. To avoid “overreactions” to individual outlying data points, we constrained the model to have minimally 10 data points between two change points (i.e., corresponding to half of the data points we collected per adult decade). We inspected the probability of number of change points and the locations of these change points (mean and 95% CrI).[[2]](#footnote-2)

## Results

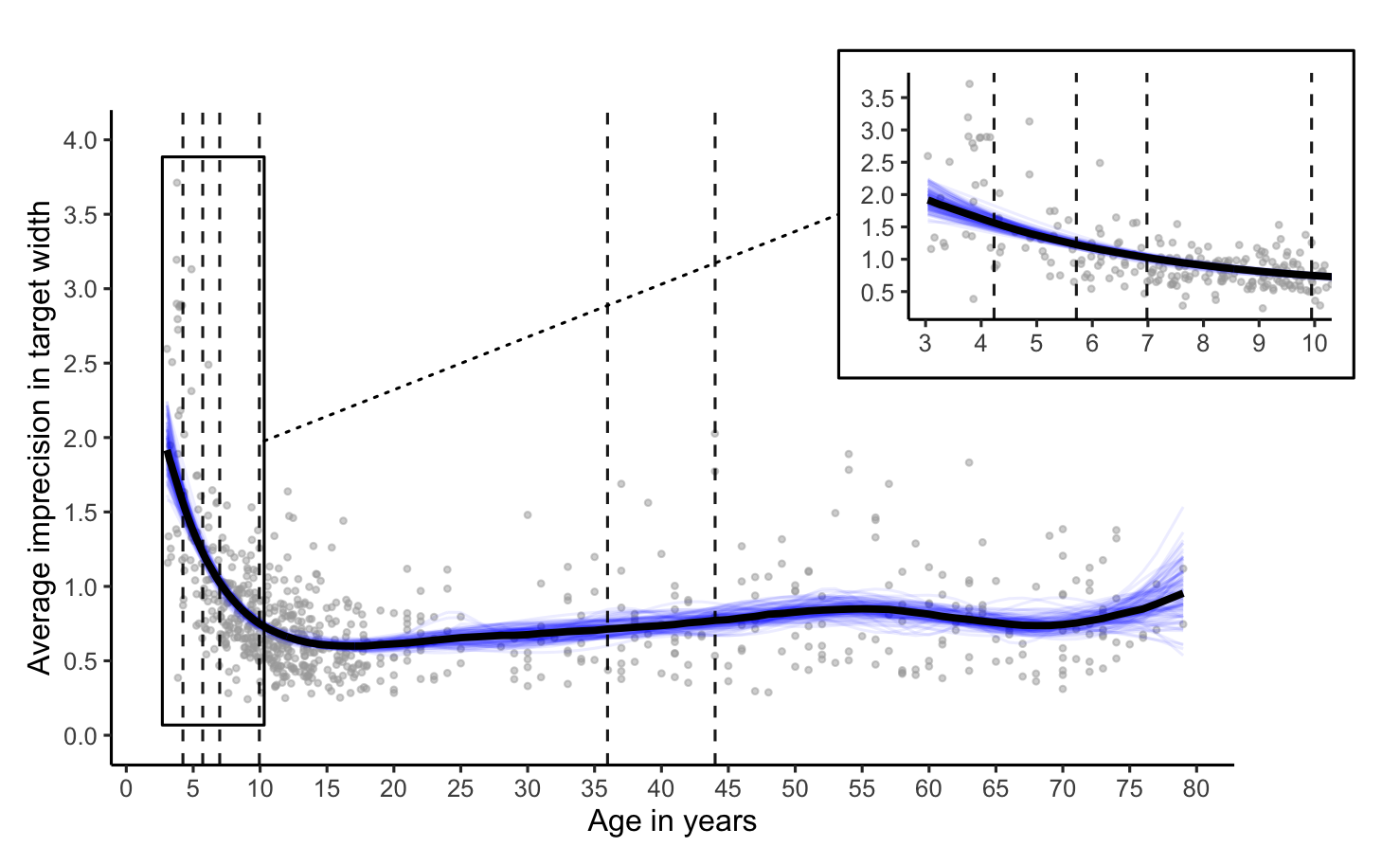


Figure 1: **Developmental trajectory of gaze understanding across the lifespan**. Performance is measured as imprecision, i.e., the absolute distance between the target’s center and the participant’s click (averaged across trials). The unit of imprecision is counted in the width of the target, i.e., a participant with imprecision of 1 clicked on average one target width to the left or right of the true target center. Grey dots show the mean performance for each subject averaged across trials. Blue lines show 100 draws from the expectation of the posterior predictive distribution (i.e., conditional expectation) 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 most prominent changes according to our Bayesian change point analysis.

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]). For example, there were some children who were more accurate than the average adult (see Figure 1).

In our model comparison, we found substantial evidence for a non-linear development in gaze understanding across the lifespan. The Gaussian process model was clearly preferred over the cubic, quadratic and linear models due to the highest predictive accuracy according to the LOO ELPD estimates (with negative ELPD differences and more than twice the estimated standard error): 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); and elpd\_diff between Gaussian process and linear model = -127.17 (SE = 18.18); all in favor of the Gaussian process model. Morover, the Gaussian Process model showed the greatest model weight (approximating 1). For the imprecision in gaze understanding, the standard deviation (*b* = 1.52, 95% CrI [0.25; 5.19]) and visual inspection indicated nonlinearity (see Figure 1).

Going one step further, we investigated the most prominent change points in the data. The Bayesian change point analysis revealed 6 (with 23.49% probability) major shifts in gaze understanding during the lifespan. The change points occurred at the following ages: 4.23 years (95% CrI [4.13; 4.33]); 5.71 years (95% CrI [5.38; 5.90]); 6.98 years (95% CrI [6.64; 8.04]); 9.94 years (95% CrI [8.66; 12.55]); 35.97 years (95% CrI [27.30; 39.69]); and finally, at 44.01 years (95% CrI [40.37; 44.43]). In other words: we found a very rapid initial improvement in early childhood, followed by a long period of minor, very slow change with slightly increasing levels of imprecision towards old age.

## Discussion

We investigated the shape of change in gaze understanding across the lifespan. One of the major strengths of our study was that we used the same task for all age groups. This allowed us to quantitatively compare performance across ages and directly model performance in relation to age. We found a non-linear developmental trajectory in gaze understanding: Early in childhood, children quickly enhanced their level of proficiency. Performance peaked (i.e., imprecision was lowest) around early adulthood, while there was a minor decay in later adulthood. This is consistent with the view that we fine-tune our existing gaze understanding ability after the first emergence in early childhood. Furthermore, we observed individual differences in all age groups. While variation was highest in the three- and four-year-olds, it remained relatively stable across the lifespan.

Previous studies found that children start to follow gaze in the second half of their first year of life (e.g., Moll & Tomasello, 2004). In our sample, three-year-olds were still rather imprecise in their gaze understanding ability. How can we explain this divergence? First of all, 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), therefore establishing a confound with 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, Nagell, & Tomasello, 1998). Silverstein, Feng, Westermann, Parise, and Twomey (2021) used a similar manipulation of subtle gaze cues without head rotation. Interestingly, they found that infants (6- to 18-month-olds) were around or just above chance for gaze following. The authors argue that this might be because infants 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 then (3) make use of this cue to guide their own behavior (i.e., touching the screen at the cued location). We measured an active location choice instead of an attention orientation. It is conceivable that three-year-olds followed the agent’s gaze but were still learning to translate this understanding into precise, active behavior. Moll and Kadipasaoglu (2013) also argue that social forms of perspective-taking evolve prior to visual perspective-taking, which only emerges within the third year of life. Children might not be interested in a differential, spatial representation of the surrounding objects: “What is of primary importance to children is to share the world of those around them. Precisely how this shared world presents itself from one specific vantage point is secondary and does not become thematic in the very early stages” (p. 6). Taken together, this might explain why some of our younger participants located the agent’s gaze rather imprecisely.

Regarding the sample of elderly adults, we expect a sampling bias to be present (Bethlehem, 2010; Gosling, Vazire, Srivastava, & John, 2004; Remillard, Mazor, Cutrona, Gurwitz, & Tjia, 2014). First, certainly not all older people have a working high-speed Internet connection or are knowledgeable and trained in its use. Second, it takes a certain amount of independence and motivation to participate in *Prolific* studies. The elderly who know how to participate in *Prolific* studies might show greater cognitive fitness and flexibility compared to their offline counterparts. Therefore, a representative sample might show a greater age decline in gaze understanding compared to our reported sample. In addition, it is noteworthy that 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.

# Study 2: Computational cognitive model

Our lifespan study showed that gaze understanding 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 understanding (Prein et al., 2023). The variation between participants was thus likely genuine and not due to random noise. Now, we aimed to understand developmental change and variation across participants on a process level. We present a theory of gaze understanding that explains how children process the available information (i.e., the agent’s eyes) to make inferences about the agent’s line of sight and its attentional focus, which leads them to identify the target position. We formalized this inference process in a computational cognitive model.

Computational modeling frameworks allow researchers to establish mechanistic explanations of psychological phenomena (Grahek, Schaller, & Tackett, 2021). As formal, mathematical accounts of the psychological process in question, they force researchers to accurately and comprehensively state all their underlying assumptions (Simmering, Triesch, Deák, & Spencer, 2010). In addition, models can be used to simulate behavior and form testable predictions. The expected patterns can then, in turn, be compared to the empirically observed behavior. Moore (2008) has already argued for systematic, empirical approaches in combination with formal modeling to arrive at a deeper understanding of gaze following.

Here, we seek to explain how participants solved the TANGO. We designed a computational cognitive model that replicates a schematic representation of how participants make inferences in the task’s context (i.e., model of the task and not the data). The fundamental assumption of this gaze model is that participants use the available gaze information to infer the target location.

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

## Computational model

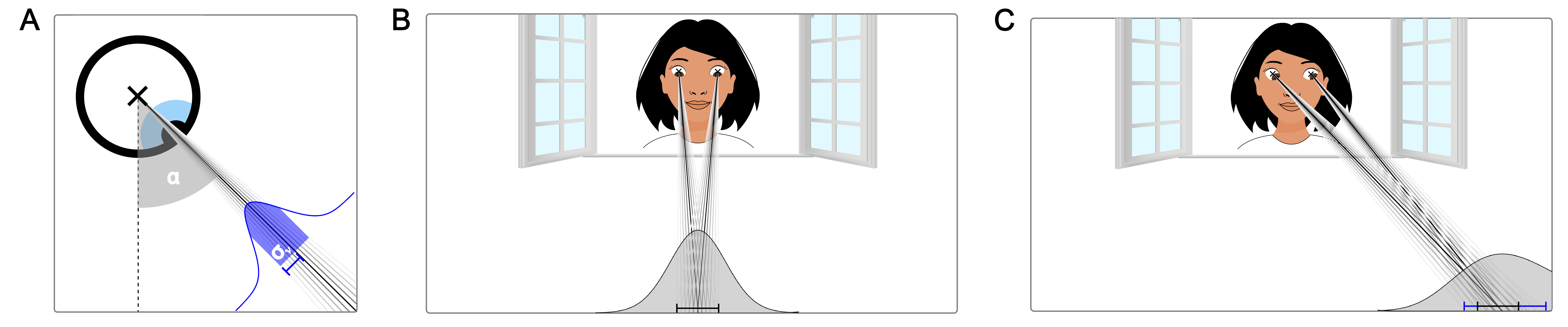


Figure 2: **Gaze model** (A) Visualization of the gaze model. Participants are assumed to observe the pupil location and estimate the center of the agent’s eye. Connecting these two point estimates as a line yields the unique vector that extends from the center of the agent’s eyeball through the center of the pupil to the attentional focal point. Taking the angle between this vector and a line pointing vertically to the ground (black dashed line) yields the pupil angle (). Participants are assumed to sample (grey lines) from Normal distributions (blue line) centered around the true pupil angle (). The variance around the Normal distribution () is centered on the true pupil angle and expected to vary between participants. (B & C) Geometrical features of the gaze model. 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. The distribution around the pupil angle 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).

Our model quantified 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:

where is an individual’s cognitive ability to locate the focus of the agent’s attention, is the coordinate the participant clicked, and and are the pupil angles for the left and right eye, respectively. The pupil angle 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).[[3]](#footnote-3)

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 ( and ) cannot be directly observed and have to be estimated based on the position of the pupils within the eyes, resulting in approximate values ( and ). 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 implied a “matched pair” of the estimated pupil angles and , 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:

The second term of the right-hand side equation above, , 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, partly 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 center of the screen) based on the data: .

The width of this distribution is defined by . For children, we assumed that the center bias changed with age and we therefore estimated via a linear regression as a function of the child’s age (): . Therefore, the participant-specific distribution for was constrained by the performance in the TANGO and the child’s age. For the adults, was not age-specific.

The main inferential task for the participant lied in estimating the pupil angles, i.e., sampling from the first term of the right-hand side equation above, . For this, we assumed that the pair of estimated pupil angles were sampled from a probability distribution which is the product of two Normal distributions of equal variance, , centered on the true pupil angles:

Broadly summarizing: Participants were assumed to observe the pupil locations and the center of the agent’s eyes. 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. Taking the angle between this vector and a line pointing vertically to the ground yields the pupil angle. Participants were assumed to sample from Normal distributions centered around the true pupil angle. They were assumed to do this independently for the left and right eye and then integrate the information to estimate the target’s location.

As determined the level of accuracy with which the participant estimated the pupil angles, it is the component that defines . When 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 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 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 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 pupil angle from which participants sample is comparatively wider than when the agent gazes centrally to the ground in front of them. 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 , 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 decreases and the cone narrows, the extent to which performance varies at different angles decreases. Therefore, our gaze model predicted that our trials vary in difficulty: participants should be more imprecise in locating the target the further out it lands, resulting in a U-shaped pattern.[[4]](#footnote-4) 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 understanding with testable predictions. In the following, we tested these predictions in children and adults.

## Participants

The sample consisted of 60 children, including 20 three-year-olds (mean age = 3.47 years, SD = 0.34, range = 3.07 - 3.97, 11 girls), 20 four-year-olds (mean age = 4.61 years, SD = 0.26, range = 4.09 - 4.98, 10 girls), 20 five-year-olds (mean age = 5.66 years, SD = 0.24, range = 5.01 - 5.96, 12 girls). Data of children was collected in kindergartens located in Leipzig, Germany. The children within each kindergarten were recruited via an internal database, where each parent priorly consented to child development studies.

In addition, we included 50 adults from our Lifespan study (mean age = 31.92 years, SD = 12.15, range = 18 - 63, 36 female). Adults were recruited over *Prolific* (Palan & Schitter, 2018). Since developmental change was minimal in our adult sample (see Lifespan study) and the cognitive models were computationally heavy, we decided to only include the first 50 adults who had completed the study.

## Procedure

We applied exactly the same procedure as in the first study, employing the continuous version of the TANGO (Prein et al., 2023). 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.

## Analysis

Our goal was to describe the inferential process of gaze understanding. Our analysis focused on the child sample. We quantified how well our gaze model explained the gaze understanding process in two ways. First, we used correlations to quantify how well the gaze model is able to recover the data. For this, we aggregated the model predictions and the data for each target bin and age group (3-, 4-, 5-years-olds, adults), and computed the coorrelation between predictions and the data. Second, we compared the predictions of our gaze model to two - very simple - alternative models that assume that 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 that participants randomly clicked on the screen and was implemented as sampling from a uniform distribution over all possible coordinates, . The center bias model assumed that participants always click at the screen center and was implemented as sampling from a Normal distribution with the the center of the screen as the mean, and one balloon width as the variance, . Note that the center bias model also predicted that imprecision should be higher for targets further out on the screen. However, compared to the gaze model, the center bias model predicted a very steep effect towards the sides, resulting in a V-shaped pattern (i.e., imprecision as the distance between the target location and the screen center). All cognitive models were implemented in WebPPL (Goodman & Stuhlmüller, 2014).

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. This factor 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 (i.e., Bayesian Occam’s razor): models with more parameters often have broader prior distributions over parameters, which might weaken potential gains in predictive accuracy. Details on models, including code to run the models, information about priors for parameter estimation, and Markov chain Monte Carlo settings, can be found in the associated online repository.

## Results

The age effects in Study 2 largely replicated those of Study 1. When comparing performance of the three- to five-year-olds in Study 1 and 2, we see a rapid improvement in gaze understanding in early childhood (see Figure 1 inset and 3A). The gaze model’s prior over potential target locations assumed that participants would be skewed to click towards the screen center. For the 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%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 (i.e., marginally wider distribution) compared to the younger children.

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 () showed that the data mean is suitable to quantify individual differences: child sample *r* = 0.95, 95%CI [0.92, 0.97], and adult sample *r* = 0.96, 95%CI [0.93, 0.98]. As can be seen in Figure 3C, the gaze model predicted a U-shaped pattern which we also observed in our data. The model comparison strongly favored our gaze model over the center bias model (child sample = 1,015.33; adult sample = 2,575.75) and the random guessing model (child sample = 388.98; adult sample = 919.03). For the child sample, we went one step further into the analysis. When correlating the observed data across all target positions with the predictions of the three models, we found a high similarity for the gaze model: *r* = 0.95, 95%CI [0.90, 0.98], while the correlations with the alternative models were substantially smaller (center bias model: *r* = 0.77, 95%CI [0.57, 0.89]; random guessing model: *r* = 0.78, 95%CI [0.58, 0.89]).

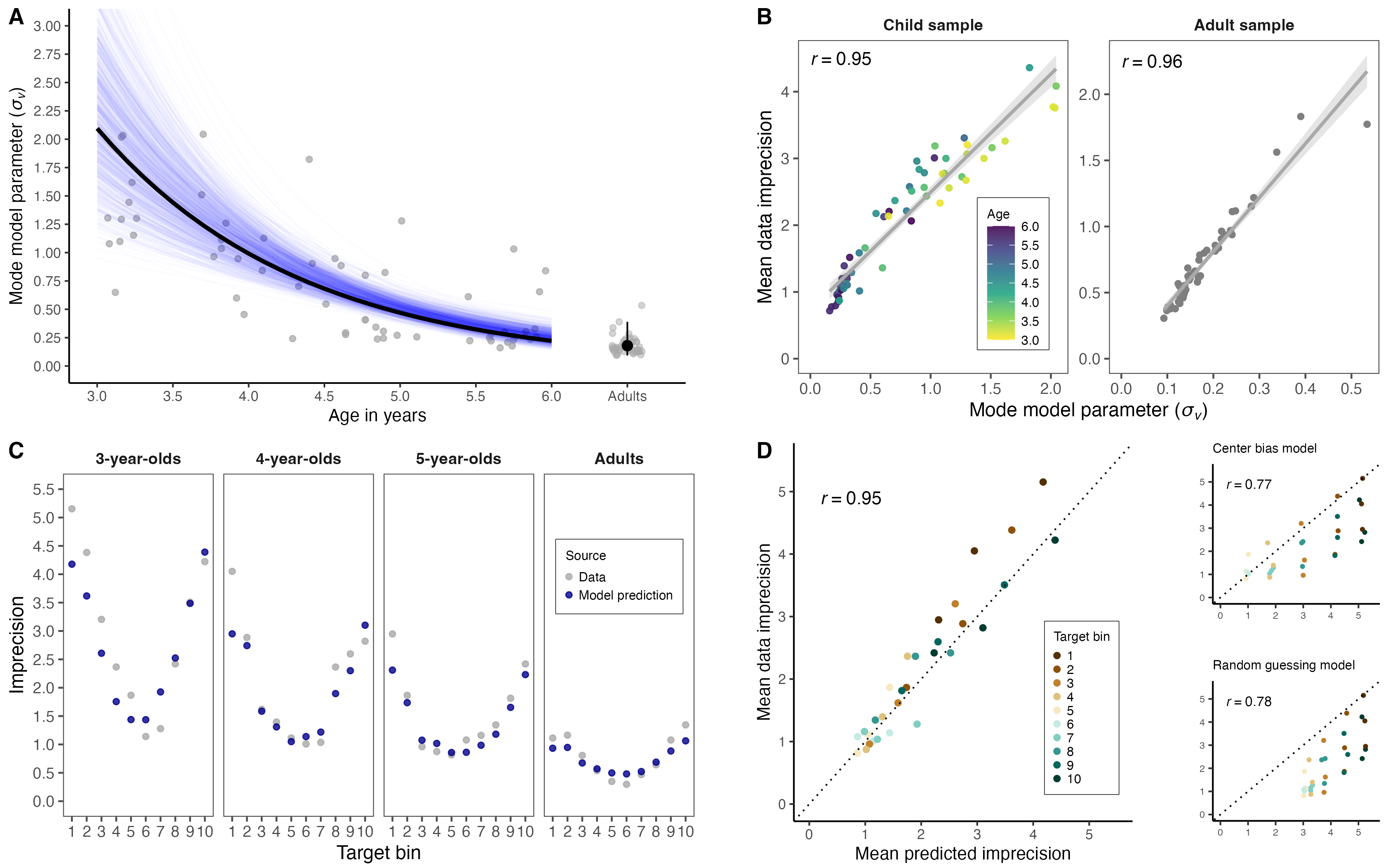


Figure 3: **Gaze model** (A) Developmental trajectory of the estimated model parameter. Grey dots show individual level parameter values. The black line shows the maximum a posteriori (MAP) estimate; blue lines show 1000 draws from it. The large black point with 95% HDI presents the mean of the model 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 the age in years. Grey 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 grey. (D) Correlation between the observed data and the predictions of the three models by target position (across age and individuals; only for the child sample).

## Discussion

Our findings from Study 1 showed individual differences and a developmental change in gaze understanding across the lifespan. To answer what develops with age and how participants differ from one another, we presented a formal cognitive model of gaze understanding.

We modeled gaze understanding 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: the target location. Individual differences can be explained as varying levels of imprecision in the pupil angle estimation. We assume the basic process of gaze understanding to be the same across the lifespan, though individuals become increasingly precise with age. By conducting model comparisons, we ruled out simpler explanations of the data.

In addition, we observed differences in performance depending on where the agent looks. The observed 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 task can be conceptually compared to the result patterns of Michelon and Zacks (2006): in their Level 1 perspective-taking visibility task, an increased distance between the agent and the target decreased performance (i.e., reaction times). Additionally, 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 axis than for those on diagonal axes (cf. “oblique effect”; (Appelle, 1972; Heeley, Buchanan-Smith, Cromwell, & Wright, 1997; Mikellidou, Cicchini, Thompson, & Burr, 2015)). Not only is our finding of increased imprecision for greater pupil angles (i.e., 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., wanting to click somewhere but experiencing motor issues at aiming, adding random noise to the click). However, the children participating in our study seemed rather determined in where they wanted to click and to not have issues with aiming or motor control (see precision in training trials). Therefore, imprecise clicking should not be a great concern.

A critical feature of our model is that it assumes gaze understanding to rely on vector estimation. In other words, 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 estimation component is a rather physical, geometrical calculation, it still happens in a social context. For example, one must interpret the agent’s eyes as a relevant social stimulus. Therefore, our computational model describes gaze understanding as a particular form of vector estimation in a social context. In the next study, we tested this prediction.

# Study 3: Components of gaze understanding

Study 3 examined the degree to which vector estimation is a part of gaze understanding. Additionally, we investigated whether there is more to gaze understanding than the physical vector estimation component. To answer this question, we assessed the relationship between gaze understanding and other social-cognitive abilities. We reasoned that gaze understanding is integral to social interaction. The positive link between TANGO and social-environmental factors like age of childcare entry (Prein et al., 2023) underlines this. Therefore, it seemed reasonable to expect correlations between gaze understanding and other measures of social-cognitive abilities.

First, we aimed to experimentally isolate the vector estimation component of the TANGO. We designed a new non-social vector estimation task that shared all crucial design features of the TANGO. Second, we assessed children’s social-cognitive abilities by administering a Theory of Mind (TOM) task battery, comprising four tasks from the ToM scale by Wellman and Liu (Wellman & Liu, 2004), and two additional perspective-taking tasks (Flavell, Everett, Croft, & Flavell, 1981; Flavell, Flavell, Green, & Wilcox, 1981). We aimed to assess whether there are exclusively task-specific processes at hand or whether gaze understanding recruits a general social-cognitive ability that is shared among other social-cognitive tasks. We reasoned that the TANGO shares task demands with the non-social vector estimation task while it shares its social context with the ToM tasks. As stated in our pre-registration, we further assessed whether the two perspective-taking tasks related to gaze understanding. Our reasoning was that similar underlying mechanisms might be needed to solve these tasks, since they ask participants to take into account another person’s point of view. This way, we aimed to disentangle what components comprise gaze understanding.

Task design, data collection, and sample sizes were pre-registered: <https://osf.io/xsqkt>. Data were collected between February and March 2023.

## Participants

Testing took place in kindergartens in Leipzig, Germany. 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.

## Procedure

Children were tested in a quiet room in their kindergarten. An experimenter guided the child through the study. Since our research questions related to individual differences and we wanted maximum control of extraneous participant variables, we employed a within-subjects study design. All participants performed the following tasks in a fixed order: (1) non-social vector estimation task, (2) ToM task battery, (3) TANGO. Several reasons motivated this decision. First, we decided on a fixed order to be able to compare participants’ performance straight-forwardly with each other. Second, to increase participant engagement and decrease fatigue or fuzziness, we switched from a tablet task to tasks with personal interaction back to a tablet task. Third, we showed the non-social vector estimation task before the TANGO so that participants would not be biased to interpret the presented stimuli as “eye- /agent-like”.

### Non-social vector estimation.

Modeling the setup and structure of the previously applied TANGO, we designed a non-social vector estimation task. This task was also presented as a web application on a tablet and made use of the concept of magnetism. The setup looked as follows. On the upper part of the screen, there was a tube with a gearwheel located in a circular window. On the floor, there was a magnet. The magnet then got switched on (making a cartoon-like sound), whereupon the gearwheel moved towards the magnet. The gearwheel moved in a way that its center aligned with the center of the magnet, 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. When no information about the magnet location was accessible, participants were expected to use the gearwheel inside the window as a non-social cue to locate the magnet.

As in the TANGO, there were three different trial types depending on the visual access to the true magnet location. In full visual access trials, the magnet’s location was presented without impediment (i.e., no wooden wall). In partial visual access trials, the wooden wall was moved in front of the target after the magnet’s location had already been visible. In test trials, participants had no visual access to the magnet’s location because the wall covered the magnet from the beginning of the trial.

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. In the experimental design process, we decided against using an arrow (or, similarly, a stick or shooting star): 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. In the case of an arrow, we would have drastically reduced the level of uncertainty and the participants would not have needed to estimate the vector anymore, since the arrow already fully displays all information (with the arrow end as the starting point and arrow tip as the “gaze” direction). Furthermore, we wanted to avoid any 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 difference between the magnet’s x coordinate and the x coordinate of the participant’s click. Magnet coordinates were generated as follows. 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. Exact coordinates within each bin were randomly generated.

### ToM task battery.

We administered four tasks from the Wellman and Liu (2004) ToM scale (see Supplements for further detail). We excluded three tasks: the Diverse Desires task in order to avoid ceiling effects; and both tasks involving emotions (Belief Emotion and Real-Apparent Emotion), as we aimed at assessing the “cold, cognitive” (as compared to the “emotional”) aspects of social cognition. Instead, we added two perspective-taking level-2 tasks (Flavell, Everett, et al., 1981; Flavell, Flavell, et al., 1981). We added the perspective-taking tasks (1) with the aim of increasing the variability we can capture between individuals, and (2) since we hypothesized that perspective-taking would rely on similar mechanisms than gaze understanding; both relying on another’s person frame of reference.

### Gaze understanding.

As in the two previously reported studies, we presented children with the continuous version of 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 understanding (<https://osf.io/tdsvc>)). This further highlighted the contrast (i.e., social vs. non-social context) to the non-social vector estimation task.[[5]](#footnote-5)

## Analysis

By design, both the TANGO as well as the non-social vector estimation task involved vector estimation. On the basis of the results from our computational cognitive model, we expected that children’s performance in both tasks would correlate with each other. For each of these two tasks, we calculated the mean level of imprecision for each subject. We then correlated these two scores using *Pearson’s* correlation coefficients.

For the ToM battery, the dependent variable was the aggregate score of all solved tasks. Regarding the relationship between the two vector estimation tasks and the ToM measures, we could imagine two possible scenarios: (A) If gaze understanding recruited a general social-cognitive ability beyond vector estimation, we expected that gaze understanding and ToM measures would correlate more strongly with each other than non-social vector estimation and ToM measures. (B) If gaze understanding relied purely on task-specific processes, then the correlation between gaze understanding and ToM measures would be comparable to the correlation between non-social vector estimation and the ToM measures. For the association between the aggregate ToM scores and the gaze understanding / non-social vector estimation tasks, we used *Spearman’s* rank correlation coefficients.

We compared the correlation between gaze understanding and ToM measures and the correlation between non-social vector estimation 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).

Furthermore, to estimate which components best explain the gaze understanding score, we conducted a model comparison with GLMMs predicting the mean imprecision in gaze understanding by age, imprecision in non-social vector estimation, 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 understanding score. As pre-registered, we hypothesized that perspective-taking seemed most closely theoretically related to gaze understanding as in both cases the participant is asked to judge another person’s point of view.

## Results

As expected, we found that gaze understanding as a social vector estimation task substantially correlated with the non-social vector estimation task, *r* = 0.38, 95%CI [0.20, 0.53] (see Figure 4B). Importantly, however, and despite the designed overlap in task demands, the two vector estimation tasks were not redundant: only a part of the variance in gaze understanding could be explained by non-social vector estimation.

Gaze understanding and perspective-taking correlated substantially, = -0.29, 95%CI [-0.46, -0.10]. Please note that the negative correlation can be explained by our outcome measure of imprecision in the TANGO (i.e., the more imprecise gaze understanding, the less perspective-taking). Non-social vector estimation and perspective-taking did not correlate, = -0.09, 95%CI [-0.28, 0.10]. However, according to the Williams’ test, these two correlations did not differ significantly from each other, *t*(99) = -1.86, *p* = 0.07.

Our model comparison revealed that gaze understanding was best predicted by a model including non-social vector estimation ( = 0.14, 95% CrI [0.06; 0.21]) and perspective-taking ( = -0.10; 95% CrI [-0.17, -0.03]), even when controlling for age ( = -0.14, 95% CrI [-0.38, 0.10]) (see Figure 4C). See Supplements for further detail of the model comparison.

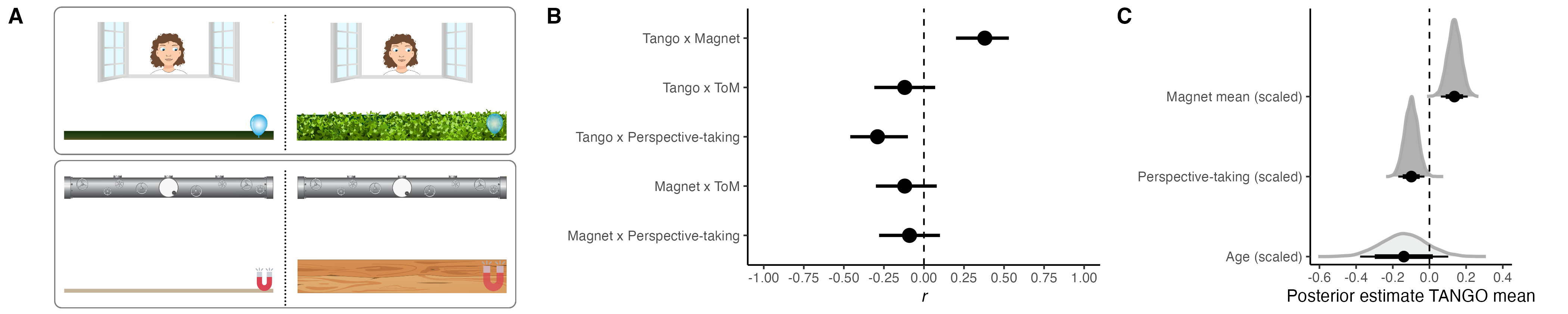


Figure 4: **Components of gaze understanding.** (A) Study procedures. Top: TANGO (i.e., gaze understanding; social vector estimation). Bottom: Magnet (i.e., non-social vector estimation). Left hand side show screenshots of familiarization phase; right hand side show screenshots of the test phase. (B) Correlations between gaze understanding, physical vector estimation, ToM, and perspective-taking. Dots show the correlation coefficients, while error bars represent 95% CIs. (C) Influence of age, perspective-taking and physical vector estimation on gaze understanding. 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.

## Discussion

Taken together, the results suggest shows that the TANGO recruited social-cognitive abilities beyond vector estimation. Evidently, it shared some of its variance with other level 2 perspective-taking tasks, while the overall ToM aggregate score did not add explanatory power.

By carefully isolating physical vector estimation experimentally, we could show that gaze understanding does indeed, to a certain degree, rely on this component. This is in line with our computational cognitive framework that assumes vector calculations on a process-level. However, physical vector estimation alone did not suffice to explain gaze understanding. In addition, perspective-taking proved to be a relevant social-cognitive ability when predicting the performance in the TANGO.

Both the TANGO and the two applied perspective-taking tasks can be seen as instances of *visuospatial perspective-taking.* According to Surtees, Apperly, and Samson (2013), perspective-taking tasks involve three components: (1) a Self (i.e., the perspective-taker), (2) the Other (i.e., a target perspective that gets judged), and (3) an Object (which is taken into perspective). Often, researchers distinguish between Level 1 and Level 2 perspective-taking tasks. Level 1 perspective-taking, also termed visual accessibility judgment, is concerned with the visibility of objects from a particular viewpoint. In these tasks, participants judge whether an object is located before or behind an agent and if this agent can see it (Surtees et al., 2013). Usually, participants can solve these tasks independently from another’s agent frame of reference and do not need to apply mental rotation (not matching the “mentalizing criterion”; (Quesque & Rossetti, 2020)). Level 2 perspective-taking, however, does rely on a mental transformation of oneself into the space of another agent. In these tasks, participants judge how (visually or conceptually) the world looks like for another person or whether an object is to their right or left. This presumably entails a simulative transformation of one’s own body schema (Erle & Topolinski, 2017). Additionally, 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. The two perspective-taking tasks we administered within the ToM scale fall into the second category.

What could drive the connection between the TANGO and the two other perspective-taking tasks? Both tasks tap into the ability to judge what another person sees. In the TANGO, participants must assume that another agent perceives and looks at the target in order to locate it. The here-applied Level 2 perspective-taking tasks add a layer by asking how one’s perspective differs from another person’s and how exactly the other person sees an object. In an intriguing series of experiments, Michelon and Zacks (2006) assessed the different processes that participants used to master Level 1 (visibility of objects) and Level 2 (object’s location relative to another agent) perspective-taking tasks. Their results suggest that participants rely on line-of-sight tracing in the former case and perspective transformation in the latter case. According to Michelon and Zacks (2006), line-of-sight tracing presumably consists of (1) locating the avatar, (2) locating the target, and (3) drawing a line from the agent to the target. Note how our gaze model in Study 2 shares the underlying idea of connecting points in space via a line. Perspective transformation presumably adds complexity and consists of: “(1) locate the avatar in an egocentric space, (2) perform a perspective transformation so that one’s imagined position matches the position of the avatar, (3) locate the target object in the transformed spatial representation of the scene, and (4) read off the coordinates of the object” (Michelon & Zacks, 2006). Therefore, the processes to solve Level 1 perspective-taking tasks might be computationally lighter since there is no need to adapt 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 differentiate 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 can work without mental states and can, therefore, be applied to non-agentive objects with a front (Surtees et al., 2013). Interestingly, computing a line of sight does not demand the presence of another agent (Michelon & Zacks, 2006). This could explain how our participants solved the non-social vector estimation task.

Interestingly, we found weaker correlations between gaze understanding and the other ToM tasks. While ToM tasks and the TANGO share the social context, the cognitive processes needed to solve each task might vary. As Rakoczy (2022) reflected, perception-goal psychology (which includes gaze understanding) 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 mutually incompatible, false, or involve fine-grained aspectual information.

In previous work, we established that the TANGO is suited as an individual differences measure (Prein et al., 2023). Capturing meaningful variability in performance 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: they relied on an aggregate score of few dichotomous items. The resulting sum scores are 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 (Białecka-Pikul et al., 2021; Byom & Mutlu, 2013; Poulin-Dubois, Goldman, Meltzer, & Psaradellis, 2023; Rakoczy, 2022; Wellman, 2018), and measures with satisfying psychometric properties are, to the best of our knowledge, still scarce (e.g., Beaudoin, Leblanc, Gagner, & Beauchamp, 2020; Mayes, Klin, Tercyak, Cicchetti, & Cohen, 1996), we nonetheless relied on them in this study. Thus, lower correlations between ToM abilities and gaze understanding could reflect poor measurement 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 a certain task 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 (stratified by target position) for the TANGO and the non-social vector estimation task (e.g., see Prein et al., 2023), we do not have reliability estimates of the ToM measures. Therefore, applying said approaches is unfortunately not feasible to compare correlations between all our applied measures. This, in turn, underlines the importance of assessing the psychometric properties of a task and the reporting of such. The development of new measures to capture individual differences in social-cognitive abilities like false-belief understanding seems desirable and essential to move this line of research further.

# General discussion

In a series of three studies, we shed light on the developmental trajectory of gaze understanding across the lifespan and the cognitive processes behind it. Study 1 focused on how gaze understanding changes with age. We found a steep learning curve in the preschool years in which children became more and 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 understanding at a process level. We modeled gaze understanding 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. Individual differences can be represented as varying 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. Study 3 made use of the case that the TANGO is a reliable individual differences measure to further investigate potential components of gaze understanding. One fundamental assumption of our computational cognitive model was that gaze understanding relies on a vector estimation process. We experimentally isolated this component by designing a non-social, physical vector estimation task. Furthermore, we assessed the relationship between gaze understanding and traditional ToM tasks. We found that gaze understanding does, indeed, share a substantial part of its variance with the non-social counterpart of physical vector estimation. In addition, perspective-taking correlated with gaze understanding, whereas the other ToM measures (focussing 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 one-year-olds can orient their visual attention toward one out of two objects, this is not the end point of development. By studying gaze understanding on a continuum, we could move beyond the pure existence of gaze understanding and assess how precisely children locate an attentional focus. Our applied measure allowed us to capture fine-grained individual differences throughout the lifespan. 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. A crucial benefit of this study is that we could use the same experimental paradigm in all age groups. This considerably lifts methodological challenges when comparing performance in a given social-cognitive task across ages.

In Study 2, we proposed a theoretical framework to interpret the development and individual differences in gaze understanding. 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; see Figure 2A). We found strong evidence for the proposed gaze model when compared against two alternative models and correlating its predictions with the observed data (see Figure 3D). Notably, the model recovers signature patterns in the data (see Figure 3C). 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 understanding equals a reduction in noise when estimating the agent’s pupil angles. Impressively, we found evidence that the same model performed well for a child as well as an adult sample.

In Study 3, we tested the relation between gaze understanding and non-social vector estimation. As implied by the structure of our gaze model, we found that gaze understanding relates to the ability to estimate vectors in space. This 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 estimation abilities.

Even though our gaze model is designed within a 2D world, we believe the mechanisms can be extrapolated into the real 3D world. The processes of understanding gaze in daily life likely rely on the same principles as proposed in this paper. We presented the first evidence that this might be the case. In Study 3, we administered a Level 2 perspective-taking task in which participants needed to adapt to 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 (i.e., screen-based vs. real-life interaction).

Clearly, our real-life environment is visually still more cluttered and diverse than the one presented in our tablet task. However, in contrast to our task, additional informational sources are available to infer where others are looking; for example, body or head orientation or common ground (Bohn & Köymen, 2018; Moll & Kadipasaoglu, 2013; Osborne-Crowley, 2020). A previously shared interaction history might restrict the options we consider potential targets. From a modeling perspective, this might be represented as a non-uniform distribution over locations in the visual scenery.

While we described the development and mechanisms behind gaze understanding, we still need to further explore the driving forces behind this development. As we have previously seen (Prein et al., 2023), precision in gaze understanding is linked to receptive vocabulary and opportunities for social interaction (e.g., number of siblings and age when entering childcare). Humans likely learn to follow gaze in social interactions (Triesch, Teuscher, Deák, & Carlson, 2006). Which exact kind of interactions are most helpful to improve precision in gaze understanding remains unknown. A promising field for future research would be to study the influence of cultural and environmental factors on gaze understanding. In addition, a next logical step for studying individual developments in gaze understanding would be longitudinal data collection.

# Limitations

In this project, we have focused on studying variation between individuals and across age groups. However, our findings rely on participants from Western, Educated, Industrialized, Rich, and Democratic (WEIRD) backgrounds (Henrich, Heine, & Norenzayan, 2010). Cultural variation has been found in many foundational aspects of cognition and socialization: for example, in parent-child interaction and communicative signals (Nielsen, Haun, Kärtner, & Legare, 2017). There is first evidence that cultural variation in face-to-face interactions does not influence infants’ gaze following abilities (Hernik & Broesch, 2019). However, we cannot generalize our here-reported developmental trajectory to different socio-environmental and cultural settings, and assume that our presented process model of gaze understanding holds universally true. Analysing cross-cultural variation and, for example, checking for predicted “signature patterns” in the data, will inform our modeling work and theory building in further detail (Amir & McAuliffe, 2020).

Moreover, is important to note that our estimation of the developmental trajectory in gaze understanding relies on a cross-sectional study. Longitudinal studies are needed to gain more confidence in the here-described developmental trajectory and to interpret the correlations between gaze understanding and other social-cognitive abilities.

Furthermore, the testing setup might have influences different age groups differentially. It is conceivable that younger children and teenagers are more trained in using a tablet. Potentially, the older adults in our sample were not as trained in its use. As mentioned in Study 1, recruiting older participants online might also select a particular subgroup of this age range. Seventy-year-olds who have working WIFI connections, know how to use a computer and are registered on Prolific might not be representative for their age group. We can imagine that results from a more diverse, in-person data collection might show different developmental trajectories towards old age.

Our computational cognitive model of gaze understanding estimates one person-specific parameter for how accurately participants locate another person’s attentional focus. The model assumes no motor imprecision in this estimation. Clearly, it could be the case that younger children 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. An argument that speaks againt motor control issues is children’s performance in the training trials. In the first trial, in which children were simply asked to touch the balloon, we found nearly perfect precision levels (also see Supplements of Prein et al., 2023). Motor issues and inaccurate aiming, resulting in falsely wide estimations in the model’s inferential component, seem therefore very unlikely.

Regarding Study 3, we matched the non-social vector estimation task as closely as possible to the TANGO. However, it is important to note that a critical feature of the target object differed between the two tasks: in the TANGO, the target (= balloon) moved from the center of the screen to its final position in a self-propelled, continuous way. In the non-social vector estimation task, the target (=magnet) did not move but stayed stationary on the ground. Two possible critiques come to mind: first, the self-propelled movement of the balloon could evoke a sense of agency, which would not be the case for the magnet. Second, the starting positions differ: the magnet never appears in the center of the screen. Keeping the starting point of the balloon in mind might be especially important when interpreting the U-shaped pattern found in Study 2. Additionally, in the TANGO, two eyes are presented and information of the two (matching) cues need to be integrated to infer the target’s location. In the non-social vector estimation 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. Future research could further investigate how factors like self-propelled movement, agency (of the cued target), spatial layout, and number of information sources influence the mechanisms of gaze understanding.

# Conclusion

In three studies, we have illuminated the development and the mechanisms of gaze understanding in further detail. We have shown that gaze understanding continues to develop beyond infancy, and that individuals differ in their precision levels to localize the attentional focus of an agent. Our proposed process-level theory proved helpful to model the mechanisms of gaze understanding and the source of individual differences. 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.

# Declarations

… can be found on the title page.

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1. Originally, our models were fitted on a trial-by-trial basis and implemented 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 Supplements for a comparison between the original and the here-reported model structures. The model predictions did not differ notably. [↑](#footnote-ref-1)
2. In a supplementary analysis, we varied the parameters of our changepoint analysis. We 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 (i.e., greater nr of change points, smaller minimum nr of data points between change points, higher polynomial order), 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 change, adults showed a relatively stable level of imprecision. There was a minor change in that elderly adults became slightly more imprecise again. See Supplements for further detail. [↑](#footnote-ref-2)
3. 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). We then calculated a line between these two points: this was our gaze vector (acting in the functionally same way as a pupil angle). Now, 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. [↑](#footnote-ref-3)
4. 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 Supplements. [↑](#footnote-ref-4)
5. In an exploratory analysis, we compared children’s imprecision levels in the TANGO task with animal vs. human agents. Based on a GLMM analysis, we conclude that there was no evidence of a stable effect of stimulus choice (human vs. animal). See Supplements for further detail. [↑](#footnote-ref-5)