Perspective-taking and social inferences in adolescents, young adults and older adults

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Author contributions

MDL contributed to study design, data collection, data analysis and interpretation, and drafting the manuscript; HJF conceived of the study, designed the study, data analysis and interpretation, and led on drafting and revising the manuscript. Both authors gave final approval for publication.

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Abstract

Taking another person's perspective provides a means to infer their beliefs and intentions (known as Theory of Mind), is an essential part of social interaction. In this paper we examined how different sub-components of perspective-taking change beyond childhood in a large sample (N=263) of adolescents, young adults and older adults, and tested the degree to which age-related changes in perspective-taking are mediated by executive functions. Participants completed three tasks that assessed, i) the likelihood of making social inferences, ii) judgements about an avatar's visual and spatial perspective, and iii) their ability to use an avatar's visual perspective to assign reference in language. Results revealed that while the likelihood of correctly inferring others' mental states increased linearly between adolescence and older adulthood (likely reflecting accumulating social experience over the lifespan), the ability to judge an avatar's perspective and use this to assign reference was subject to developmental changes from adolescence to older age, with performance peaking in young adulthood. Correlation and mediation analyses incorporated three measures of executive functioning (inhibitory control, working memory, and cognitive flexibility) and revealed that executive functions contribute to perspective-taking ability in these tasks (particularly during development), but largely do not mediate the effect of age on perspective-taking. We discuss how these results fit with models of mentalising that predict distinct patterns of social development depending on the maturation of cognitive and language mechanisms.

Keywords: theory of mind, perspective-taking, aging, social development, cognition, adolescence

1. Introduction

Social interaction requires us to understand and interpret observable behaviour (Frith & Frith, 2007; Kanske & Murray, 2019), and therefore comes under a more general 'umbrella' concept, known as Theory of Mind (ToM; Wimmer & Perner, 1983). ToM is the ability to understand and predict other peoples' mental states, including their desires, beliefs and intentions (Premack & Woodruff, 1978; Baron-Cohen, 1997). One important means through which we can infer others' mental states is by taking their perspective, in other words adopting someone else's visual or spatial viewpoint to assess *what* they can see or *how* they see it. Given the importance of these skills for successful social development, a great deal of research has focused on how ToM develops across childhood (Leslie, 1987; Premack & Woodruff, 1978; Wellman, 1991, 1992). It has been suggested that from around the sixth year of life, children possess a sophisticated adult-like ToM, and are able to distinguish their own mental state from others' (Mossler, et al., 1976; Perner et al., 1987). In this paper we focus on the developmental trajectory of perspective-taking beyond these early years of childhood by testing perspective-taking abilities in a large sample across three age groups: adolescents (aged 10-19 years old), young adults (aged 20 to 40 years old) and older adults (aged 60 to 80 years old).

Over the past couple of decades, new paradigms and methodological advances have facilitated a new body of research that has examined social interaction beyond childhood. This work has demonstrated that social development continues through adolescence and well into our twenties (e.g. Blakemore, 2008; Dumontheil et al., 2010), that even healthy adults can experience difficulties considering another person's point of view when that view conflicts with their own (e.g. Apperly et al., 2008; Birch & Bloom, 2007; Keysar et al., 2000), and that specific impairments in these abilities emerge with increasing age (e.g. Bailey & Henry, 2008; German & Hehman, 2006; Phillips et al., 2011). However, there is uncertainty regarding the task or domain-specificity of age-related social impairments, with affective ToM appearing to be relatively spared in older adults (e.g. Bottiroli et al., 2016; Castelli et al., 2010; Henry et al., 2013; Mahy et al., 2014; Pardini & Nichelli, 2009), and subjective experience of ToM showing no effects of age (which suggests an age-related impairment in metacognition; Duval et al., 2011). It is therefore likely that early studies have overlooked key stages in the development of social interaction skills that extend beyond the childhood years. In this paper we focus on three aspects of perspective-taking to assess how these abilities change with age: mental state inferences, visual/spatial perspective-taking, and reference assignment. Thus, we test the general hypothesis that perspective-taking is enhanced among young adults compared to both adolescents and older adults.

The ability to take other peoples' perspectives, infer their mental states, and use this knowledge to generate expectations about their behaviour are closely related processes that are fundamental to social interactions; they all help us to understand others' intentions and beliefs. However, they make distinct contributions to ToM. Perspective-taking is a means through which people can infer others' mental states (i.e. by adopting their point of view, or their visual perspective), and can be activated relatively spontaneously (O'Grady et al., 2020; Samson et al., 2010). Social inferences about other people (e.g. what they think, want or feel) influence impression formation, and can be executed either while directly observing behaviour, or at a later point, from a memory record of this observed behaviour or other information (Apperly, 2010). In their most basic forms, mental state inferences occur rapidly and spontaneously (Ferguson et al., 2015; Kruse & Degner, 2021), and require only minimal attention and cognitive resources (Todorov & Uleman, 2003; Wells et al., 2011). In contrast, the capacity to *use* knowledge about others' perspectives and mental states requires the use of "higher-order" representations of the mind (Frith & Frith, 2006; Davies & Stones, 1995; David et al., 2008), and is known to be more cognitively demanding and under cognitive control (Ferguson et al., 2015). These distinctions raise the question of whether different sub-components of perspective-taking and social inferences are affected differently by aging.

Research suggests that the ability to make mental state inferences first emerges with intentionality (6-18 months), followed by desire (2nd year), then belief (4th year), and personality (6th–7th year; Kalish & Shiverick, 2004; Wellman et al., 2001; Wellman & Woolley, 1990; Woodward, 1998). A large body of evidence has now demonstrated that young adults quickly and readily infer mental states for other people from their behaviour, including their traits, goals and social roles (e.g. Chen, Banerji, Moons, & Sherman, 2014; Uleman, Saribay, & Gonzalez, 2008). Research has distinguished young adults' ability to make inferences about others' perspectives from the ability to *use* this information to predict their behaviour, with the former occurring earlier and with less cognitive effort than the latter (Ferguson et al., 2015). Nevertheless, compared to young adults, older adults show impairments in identifying mental states (Henry et al., 2013), and fail to take account of intentions when judging moral permissibility (Moran et al., 2012). For example, using a series of videos depicting everyday life situations, Lecce et al. (2019) showed that older adults were impaired in identifying and discriminating scenarios that involve mental states from those that do not require them; older adults often reported mental states when they were not present or failed to detect mental states when they were. However, some studies have shown that older adults are *more* sensitive than younger adults to cues that facilitate social inferences (Hess, Osowski, & Leclerc, 2005; Hess, Rosenberg, & Waters, 2001), and that this sensitivity does not relate to basic cognitive skills (Leclerc & Hess, 2007; Hess, 2014), which suggests that accumulating social expertise over the lifespan might actually improve the ability to make social judgements.

The presence of a human avatar has been shown to influence perspective-taking (Samson et al., 2010; Baker et al., 2016; Furlanetto et al., 2016; Todd et al., 2017), suggesting that another person's view is spontaneously processed at an implicit level (Epley et al., 2004b; Samson et al., 2010; Surtees & Apperly, 2012). In fact, research has revealed that people experience interference from their own point of view when adopting an avatar's perspective (egocentric intrusion; Epley et al., 2004b; Keysar et al., 2003) as well as interference from the avatar's point of view when judging their own perspective (altercentric intrusion; Qureshi et al., 2010; Todd et al., 2017). Perspective-taking can be considered on several dimensions. Visual perspective-taking describes *whether* and *how* another person can see an object, and spatial perspective-taking describes *where* an object is located in relation to another person. In addition, judging *what* another person can see (level 1 perspective-taking) is distinct from judging *how* a person perceives something (level 2 perspective-taking); level 2 judgements typically require mental rotation, whereas deciding what a person can see does not (Surtees, et al., 2013a, b). While an egocentric intrusion occurs when judging what and how a person can see something (both level 1 and 2), an altercentric intrusion seems to occur in level 1 but not level 2 (Samson et al., 2010; Surtees et al., 2016; but see also Mattan et al., 2017). Related to this, research has shown that perspective calculation is more cognitively efficient for level 1 than level 2 perspective-taking (Edwards & Low, 2019; Todd, Simpson, & Cameron, 2019; Qureshi, Apperly, & Samson, 2010). Developmental studies show that knowledge about *what* another person can see appears in early childhood (14 months; Flavell et al., 1981; Masangkay et al., 1974; Sodian et al., 2007), with 2-year-old children successfully passing tasks that tap this understanding (Moll & Tomasello, 2004). In contrast, the ability to comprehend *how* a person perceives something emerges around 4 years of age (Flavell et al., 1981) and continues to improve through early childhood (Frick et al., 2014; Surtees & Apperly, 2012). Few studies have investigated perspective-taking in older age, however those that have revealed impairments in switching from their own perspective to the on-screen avatar's (altercentric) visual perspective (Martin et al., 2019), and a preference to adopt a self-relevant perspective (Mattan et al., 2017).

Finally, perspective can be used to guide reference when interpreting instructions. In the so-called 'director task' (referred to here as the interactive reference assignment task), participants follow the instructions of an on-screen avatar to move objects around a grid. Importantly, some of those objects are occluded from the speaker's but not the participant's view, leading to a discrepancy in the two communicators' perspectives (shared *vs.* privileged) and thus ambiguity in reference assignment. Typically, participants make more errors on privileged trials as they fail to adopt the speaker's perspective and interpret reference according to their own egocentric perspective (e.g. Ferguson & Cane, 2017; Dumontheil et al., 2010; Keysar et al., 2000; Meyer et al., 2015; Mills et al., 2015; Santiesteban et al., 2015). Epley et al. (2004b) suggest that people make judgements about others' perspective by first anchoring to their own point of view and only later adjusting it to fit with the other person; this adjustment requires cognitive effort. Research that has examined the developmental trajectory of perspective-taking in this task has shown that children (4 to 12 years) and adolescents commit more egocentric errors compared to young adults, however no age differences emerged in terms of response time (Choudhury et al., 2006; Dumontheil et al., 2010; Epley et al., 2004b; Symeonidou et al., 2016). Even in healthy adults, inferring other peoples' perspectives in the interactive reference assignment task is cognitively effortful and subject to interference from our own point of view (Cane et al., 2017; Keysar et al., 2000). Only one published study has used this task to examine how referential perspective-taking changes in older age and found that older adults were less likely to use perspective information to differentiate the target from the competitor object (Saryazdi & Chambers, 2021).

Over the last decade or so, there has been increasing speculation about the degree to which cognitive mechanisms (i.e. executive functions (EFs)) mediate successful social interaction, including whether the age-related changes in social skills described above reflect established changes in cognitive performance across the lifespan (Diamond, 2002; Salthouse, 2009) rather than impairments in the ToM mechanism itself. This relationship make sense given that successful perspective-taking requires one to hold in mind multiple perspectives (i.e. working memory), suppress irrelevant perspectives (i.e. inhibitory control), and switch between these two perspectives depending on context (i.e. cognitive flexibility). Accordingly, the majority of new psychological theories and reviews that aim to explain social cognitive phenomena, including their developmental trajectory, have explicitly reflected on this relationship (e.g. Apperly & Butterfill, 2009; Apperly, 2009; Carruthers, 2016; Wade et al., 2018; Weimer et al., 2021). Accumulating empirical evidence has also demonstrated a key role for EFs as part of a shared network that supports social interaction, even in healthy adults (e.g. Bradford et al., 2015; Bull, Philips, & Conway, 2008; Cane et al., 2017; Lin, Keysar, & Epley, 2010; Schneider, Bayliss, Becker, & Dux, 2012).

In early childhood, a robust relationship exists between the acquisition of EFs and improvements in ToM skills, independent of age and IQ (e.g. Carlson et al., 2004; Perner & Lang, 1999). During adolescence, structural and functional progressions in the social brain are known to interact with improvements in cognitive control (Blakemore & Mills, 2014; Dumontheil, 2016; Humphrey & Dumontheil, 2016; Mills et al., 2015). In older age, there is mixed evidence for the mediating role of EFs as some studies show a relation between age-related ToM decline and EFs (e.g. German & Hehman, 2006; Moran, 2013; Phillips et al., 2011; Rakoczy et al., 2012), and others show none (e.g. Cavallini et al., 2013; Maylor et al., 2002). These patterns suggest that success in social interaction might vary depending on the demands placed on EFs and language, both of which are subject to age-related change, and that social cognitive skills might be spared from age-related decline when they make minimal demands on EFs. For example, basic social inferences that do not rely on cognitive abilities can be activated spontaneously, even in early childhood and into older age. In contrast, more sophisticated forms of social interaction (particularly those that involve language) continue to develop through childhood and adolescence and decline in older age since they rely on increasingly complex cognitive mechanisms that develop over a protracted period into early adulthood (Best & Miller, 2010; De Luca et al., 2003) and decline in later life (Gunning-Dixon & Raz, 2003; Phillips, Henry, Hosie, & Milne, 2008).

Another critical issue in research on social interaction arises from the fact that the majority of studies administer only a single task to measure social abilities (e.g. Alvi et al., 2020; Mohammadzadeh et al., 2020; Stack & Romero-Rivas, 2020), despite major debates over task validity in this field. In a recent study by Warnell and Redcay (2019), correlations between ToM tasks within various age groups revealed minimal relations between tasks, with Bayesian analysis indicating the null hypothesis was more likely (i.e. no relationship between tasks) once age and verbal IQ were controlled for. Similarly, Morrison et al. (2019) found minimal to moderate correlations between ToM tasks in a typically developing adult population, and Gallant et al. (2020) discovered that many of the relations between ToM tasks disappeared in 4-6 year-olds once language and age were controlled for. A recent study by Navarro and colleagues (2020) employing psychometric modelling also found only a subtle relationship between two ToM tasks. The minimal correlations between tasks in these studies indicates a lack of convergent validity of ToM tasks (Gallant et al., 2020; Hayward & Homer, 2017; Schaafsma et al., 2015), and reinforces the importance of employing multiple measures to capture the different sub-components of ToM. In addition, very few studies include participants of varying developmental stages (i.e. throughout childhood, adolescence, and adulthood), and those that do typically employ different batteries of social tasks for different age groups in order to avoid ceiling effects. This makes it difficult to fully understand whether group differences, and the contribution of EFs, are affected by task differences or genuine developmental changes.

In this paper, we adopted three measures of perspective-taking to assess how the ability to make mental state inferences, take others' visual/spatial perspective, and assign reference change with age. We assessed mental state inferences using the 'hierarchy of social inferences' task developed by Malle and Holbrook (2012), in which participants watched short videos and inferred basic mental states for the characters. Malle and Holbrook found that the young adults in their study judged intentions and goals easier and faster than beliefs, followed by personality. We examined whether the general propensity to infer social states changes across the lifespan (i.e. reflecting an overall decline in ability to attribute beliefs and intensions to others in older age) and also whether the hierarchy of making different types of social inference changes across development (we did not predict any age-related differences in this hierarchy since basic social inferences are thought to be relatively effortless, and would be comparably impacted by age). To assess perspective-taking abilities, we adopted a task developed by Surtees et al. (2013a) in which the content of judgement (visual *vs.* spatial) was crossed with the type of judgement (level 1 *vs.* level 2) to examine whether developmental changes differentially impact different components of perspective-taking. We predicted that the difficulty associated with level 2 perspective-taking would be significantly larger in adolescents and older adults compared to young adults (i.e. the level 1-level 2 difference would be smaller in young adults), since calculation of *what* another person sees is relatively spontaneous but *how* they perceive it is more cognitively effortful. To investigate reference assignment, we used the abovementioned interactive reference assignment task to examine whether the ability to interpret a speaker's instructions from their perspective changes with age. We predicted that the ability to use the speaker's perspective to infer their referential meaning would be impaired in adolescents and older adults compared to young adults, due to the high demands this task places on executive functions and language. More specific predictions are detailed for each task in the Methods.

In their comprehensive review of the corelates and antecedents of ToM, Weimer et al. (2021) highlighted the need for future studies to examine developmental changes in ToM alongside different sub-components of EF abilities, to assess how the ToM-EF relationship varies by task complexity and age. Given the key roles they play in social cognition (detailed above), we assessed individual differences in three EF components: working memory, inhibitory control and cognitive flexibility, and used mediation analyses to assess the degree to which age-related changes in the different sub-components of perspective-taking could be predicted by these three EF skills.

2. Method

2.1 Participants

A total of 274 participants, aged between 10-80 years old, were recruited for this study as part of a larger longitudinal project. Of this total sample, nine participants were excluded for having Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005) scores less than 26. This resulted in a final sample of 263 participants, divided into three age groups: 87 adolescents (aged 10-19 years), 88 younger adults (aged 20-40 years), and 88 older adults (aged 60-80 years). Participants were paid for their time. All were native English speakers, had normal or corrected-to-normal vision, had no known neurological disorders, and no mental health or autism spectrum disorder diagnoses. Participants were recruited from a community sample in the local area of Kent, U.K., using a variety of recruitment strategies (e.g. newspaper adverts, local groups, word-of-mouth, Kent Child Development Unit). Sample size was based on previous research, and constraints to complete the PhD. The

Ethical Committee of the School of Psychology, University of Kent, U.K., approved the study.

Participant details, including mean age and gender balance for each of the three age groups, are presented in Table 1. Socio-economic status (SES) was estimated by asking participants (if aged over 18) or parents of participants (if aged under 18) to report on their level of education, household income, and their occupation (job title and industry). Household income was coded according to seven income bands (>£9,999; £10,000 - £19,999; £20,000 - £29,999; £30,000 - £39,999; £40,000 - £49,999; £50,000 - £69,999; £70,000 +). Occupational class was coded using the derivation tables provided by the Office for National Statistics (ONS, 2017) using the simplified National Statistics Socio-Economic Classification based on Standard Occupational Classification 2010. To calculate an SES index, education level was coded on a scale of 1-6 (from No qualifications – Postgraduate Degree), and household income and occupational class were coded on a scale of 1-7. These three scores were summed to derive an SES index between 3 and 20, with lower scores indicating lower SES; in our sample scores ranged from 3 to 17. In addition, IQ was assessed using the Wechsler Abbreviated Scale of Intelligence – Second Edition (WASI; Wechsler, 1999), cognitive dysfunction was screened using the MoCA, and autistic traits were screened using the Autism Quotient-10 (AQ-10; Allison, et al., 2012).

Table 1: Participant characteristics by age group (mean values, with standard deviations in parenthesis). IQ scores use age-standardised norms.

	Adolescents	**Younger Adults**	**Older Adults**
N	87	88	88
Age (years)	14.6 (3.0)	27.0 (5.3)	67.9 (5.2)
Gender (F:M)	49:38	60:28	58:30
SES Index	10.4 (3.3)	10.8 (2.6)	11.3 (2.4)
Full Scale IQ	102.7 (10.3)	101.3 (13.5)	110.4 (11.2)
Verbal IQ	100.9 (9.1)	99.4 (10.8)	107.6 (12.4)
Perceptual Reasoning IQ	105.2 (11.8)	102.7 (12.1)	110.6 (13.3)
MoCA	27.9 (1.9)	27.8 (1.7)	27.3 (1.8)
AQ-10	2.7 (2.0)	3.2 (1.9)	2.6 (1.5)
Working Memory (partial Ospan score)	64.1 (13.1)	66.4 (12.8)	58.4 (13.6)
Inhibitory Control (% go/no-go accuracy)	84.7 (9.4)	91.5 (5.8)	91.0 (9.2)
Cognitive Flexibility (*N* perseverative errors)	7.4 (5.9)	4.5 (4.0)	7.4 (8.1)

2.2 Measures of Perspective-taking

2.2.1 Hierarchy of Social Inferences

We adopted the task developed by Malle and Holbrook (2012; Study 3) to examine the likelihood and speed with which people make mental state inferences about others, such their intentions, desires, beliefs and personality. Stimuli consisted of 42 videos that depicted people in everyday life situations and portrayed three classes of behaviours: goal-tailored (based on intentionality, e.g. a student riding his bicycle to university), trait-tailored (based on disposition, e.g. takes an orphan to the circus), and untailored (that elicited various inferences, e.g. a woman sweeping the floor). The videos ranged in length from 4 to 12s (M = 7s). Participants were instructed to make a judgement for each video about whether or not they detected a specific mental state in the main character's behaviour (note that some trials included a control or catch cue that did not require a mental state inference and served as an attention check, see Table 2). A probe word, presented after each video, indicated the mental state to be inferred. As shown in Table 2, and in line with Malle and Holbrook (2012), social inference probe words were: THEGOAL? (for desire inferences), THINKING? (for belief inferences), PERSONALITY? and INTENTIONAL?.

Table 2: Inference probes and their meanings in the hierarchy of social inferences task.

Probe word	***Question***
PERSONALITY	Did you detect a certain PERSONALITY characteristic the main actor has?
THEGOAL	Did you detect a certain GOAL the main actor has?
THINKING	Did you detect what the main actor was THINKING (was aware of, knew, saw, etc.) in this situation?

INTENTIONAL	Did you detect the actor INTENTIONALLY perform the behaviour?
ISMALE	Is the actor MALE?
DONOTRESPOND	When you see this cue, DO NOT answer

Each trial began with a central fixation cross for 1000ms, followed by the video, then a probe word appeared for 4000ms. Participants responded to the probe word using the keyboard. If they detected the probe social behaviour, they pressed the y key, which initiated a second screen asking them to explain their answer out loud (spoken responses were recorded using a microphone and later transcribed to verify accuracy of the social inference and eliminate incorrect responses before analysis). If they did not detect the probe social behaviour, they pressed the n key, and the trial ended. See Figure 1 for an example of event sequence for trials in this task.

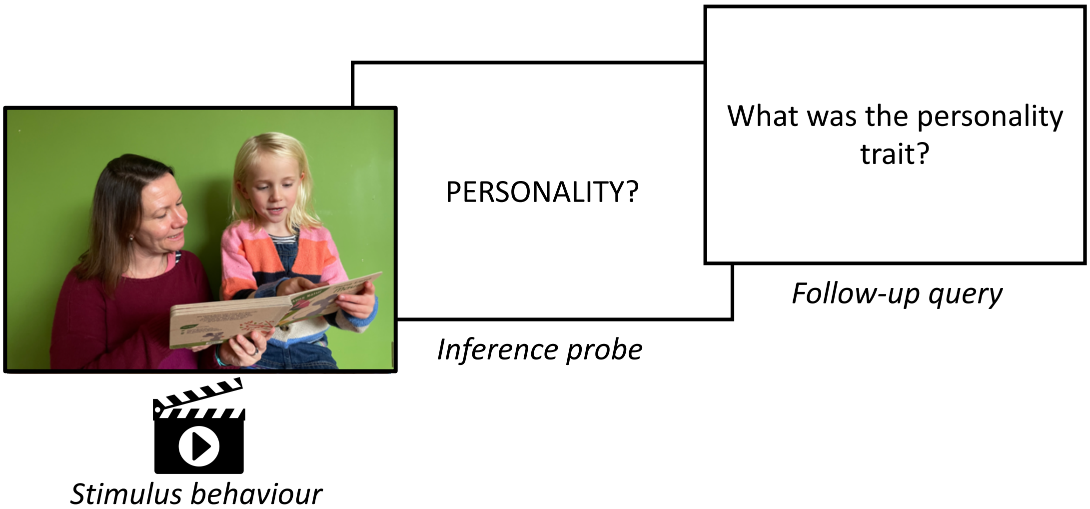


Figure 1: Event sequence for one trial in the hierarchy of social inferences task. Note: example stimuli image for illustration only; for real stimuli please see Malle and Holbrook (2012).

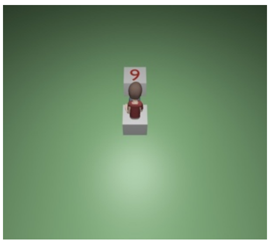
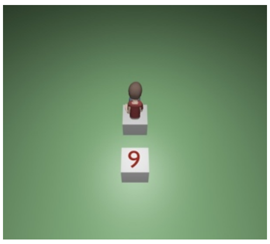
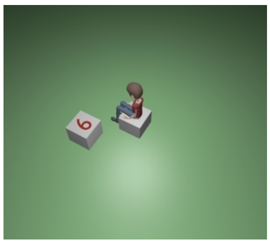
The experiment began with a familiarisation phase to ensure that participants understood the meaning of the inference probes. Participants were presented with each of the six probe words and had to say out loud the meaning, then were given the correct meaning again on screen. The main experiment consisted of a short practice block of eight trials, followed by 42 experimental trials divided into two blocks. Each of the four social behaviour probes appeared nine times during the experiment, while the catch and control probes appeared three times each. This task lasted 12 minutes on average.

The dependent variable was the likelihood of correctly making a social inference, and this was analysed using a mixed ANOVA that crossed the between-subjects factor Age Group (adolescents *vs.* young adults *vs.* older adults) and the within-subjects factor Inference type (intention *vs.* desire *vs.* belief *vs.* personality). As in Malle and Holbrook (2012), likelihood was calculated as the percentage of trials on which participants responded "yes" that they detected a social behaviour, and their verbal response confirmed a correct social inference was made. Overall, we expected to replicate previous results from Malle and Holbrook in which participants showed a 'hierarchy of social inferences'; likelihood of correct inferences would be higher for intentions and desires, compared to beliefs, and finally personality. Regarding age effects, we expected all three age groups to show the same hierarchy of social inferences, since basic inferences about others are thought to be made relatively spontaneously, and without a great deal of cognitive effort. We also tested whether overall differences in the likelihood of correctly making social inferences might emerge between age groups, either reflecting general problems attributing beliefs and intentions to others in older adulthood (i.e. reduced likelihood of making social inferences) or accumulating social expertise over the lifespan (i.e. increasing likelihood of making social inferences).

2.2.2 Visual/Spatial perspective-taking

Perspective-taking was assessed using the Visual/Spatial perspective-taking task developed by Surtees et al. (2013a). Stimuli showed a human avatar seated in a room with a cube that showed a number- 6 or 9. Each image was presented individually in the centre of the computer screen, sized at 25.4cm (W) x 22.6cm (H) (720x640 pixels). The cube could be positioned either in front, behind or to the side of the avatar, and the entire scene was presented to participants at different rotations (0°, 60°, 120°, 180°, 240°, 300°), as shown in Table 3. This design allowed us to assess both visual perspective-taking (i.e. whether and how the number on the cube is seen by the avatar) and spatial perspective-taking (i.e. the relative spatial locations between the avatar and the cube), and to judge WHAT the avatar could see (level 1: that the avatar might not see the cube that the participant sees) or HOW the avatar could see the cube (level 2: that the avatar might see the number/cube in the same form that the participant sees).

<u>Table 3</u>: Difficulty levels used in the Visual Spatial perspective-taking task. These image stimuli were used with permission from Surtees et al. (2013a).

	Level 1		**Level 2**	
	He CAN or CANNOT SEE the block		He sees a 6 or 9 on the block	
Visual				
Spatial	The block is IN FRONT or BEHIND him		The block is to his LEFT or RIGHT	

In the level 1 visual perspective-taking condition, participants were asked to judge if the avatar can see or cannot see the cube. In the level 2 visual perspective-taking condition, participants had to indicate if the avatar can see the number 6 or 9. In the level 1 spatial perspective-taking condition participants responded if the cube was in front or behind the avatar, while in the level 2 spatial perspective-taking condition they had to judge if the cube was on the avatar's left- or right-hand side. Thus, both level 1 conditions used the same set of images but gave different instructions to participants. In level 2 all the images contained instances in which the cube was visible to the avatar. For the two level 1 conditions and the level 2 visual perspective-taking condition the cube was either directly in front or directly behind the avatar, while in the level 2 spatial perspective-taking condition the cube was at a 45-degree angle from the avatar so a judgement could be made if the cube was on the left- or right-hand side of the avatar. Participants indicated their response to each trial using the up and down arrow keys on the keyboard.

Participants completed a total of four blocks (one for each condition), each consisting of 16 practice trials and 64 test trials. Angles 0° and 180° appeared 16 times each per block, and angles 60°, 120°, 240°, 300° appeared 8 times each; for analysis, the data from the 60° rotation was combined with data from the 300° rotation, and data from the 120° rotation was combined with data from the 240° rotation to include both clockwise and anticlockwise variations. The order of the four blocks, as well as the order of appearance of images within each block, was randomized. Each trial began with a central fixation cross for 600 ms, followed by 200ms blank screen and then stimulus presentation. Participants were given

5000ms to respond. If no response was recorded, the trial was coded as incorrect and next trial began automatically. Feedback on accuracy and response speed was provided during the practice blocks only. This task lasted 10 minutes on average.

Log reaction times for correct responses were analysed using a mixed ANOVA, crossing the between-subjects factor age Group (adolescents *vs.* young adults *vs.* older adults) with the within-subjects factors Angle (0° *vs.* 60° *vs.* 120° *vs.* 180°), Type (level 1 < level 2) and Content (visual < spatial). We expected to replicate previous studies (Surtees et al., 2013a) in showing main effects for level (level 2 *vs.* level 1), angle (increasing RTs with increasing angle), and content (visual *vs.* spatial), as well as interactions for angle by level, and content by level. Regarding age differences, we predicted that the speed with which participants adopted the avatar's visual/spatial perspective would decrease from adolescence to young adulthood, and increase again through old age, reflecting general changes in processing speed. Importantly, we predicted that adolescents and older adults would show greater disruption for level 2 perspective-taking (i.e. a greater difference in response times between level 1 and level 2 conditions) compared to young adults, since the process of judging how someone sees something is more cognitively effortful than the relatively efficient process of judging what they see, and is therefore more affected by cognitive development/decline. In addition, we tested whether these age differences on the effect of level increased at larger angles of rotation.

2.2.3 Interactive reference assignment

To examine participants' ability to infer reference in conversation we used an avatar version of the interactive reference assignment task (Keysar et al., 2003). The task was delivered and controlled using SR Research Experiment Builder software (version 2.1.140). During the task, participants were presented with an image of a room containing a 4 x 4 gridded cupboard, creating 16 slots that could contain objects, and a female avatar (the 'director') standing to the rear right-hand side of the cupboard (see Figure 2). Crucially, the backs of five slots (different for each trial) were covered with a green backing, so that only the participant could see the contents of these spaces, and the contents were occluded from the director's view. Eight objects were randomly placed within the grid slots, two of which were in occluded positions and six could be seen by both the director and the participant. Participants were asked to move objects around the grid following the avatar's verbal instructions.

In the Listener perspective condition, participants (the listeners) held privileged information about a competitor object in an occluded slot, and needed to take the director's perspective to select the mutually available object and ignore this competitor object (since it could not be seen by the director). Thus, participants were required to inhibit their own perspective to select the correct object from the director's point of view. For instance, the participant could be asked to 'Move the small star one slot down', where the grid contained three stars of different sizes, the smallest of which was occluded from the director. In this example, it would be correct for the participant to select the medium sized star, since this is the smallest star from the director's perspective. In the Shared perspective condition, the competitor object was replaced by a different (neutral) object that could not be mistaken for the object in the director's instruction. For instance, the participant could be asked to 'Move the small star one slot down', where the grid contained only two mutually available stars. Here, it would be correct to select the objectively smallest star, since this matched both the participant's and the director's perspective. Participants responded using the computer mouse to select an object and drag it to the new location detailed in the verbal instruction (the object moved in real-time). See Figure 2 for a visual depiction of stimuli across Listener-Only and Shared-Perspective conditions.

Prior to beginning the task, standardized instructions were presented to participants emphasising that the director had a different perspective of the grid than that of the participant; they were shown an example stimulus, including viewing the shelves from the participant and the director's perspectives (i.e. with the occluded slots blocking view of the objects inside of them from the director's perspective), to ensure all participants understood that the director could not see all the objects.

The main experiment included two practice trials and 24 experimental trials (each with a different set of objects), of which 12 included a Listener perspective instruction and 12 included a Shared perspective instruction. Each trial included two instructions; one was a filler that referred to a specific item and did not involve perspective-taking (e.g. 'Move the yellow bucket one slot up'). Filler instructions were not included in the analysis. The order of filler and critical instructions was counterbalanced across trials, and a new instruction was only given once participants had responded to the previous instruction. Audio instructions were presented through headphones, and participants were given 4000 ms before the first instruction to inspect the grid. This task lasted 10 minutes on average.

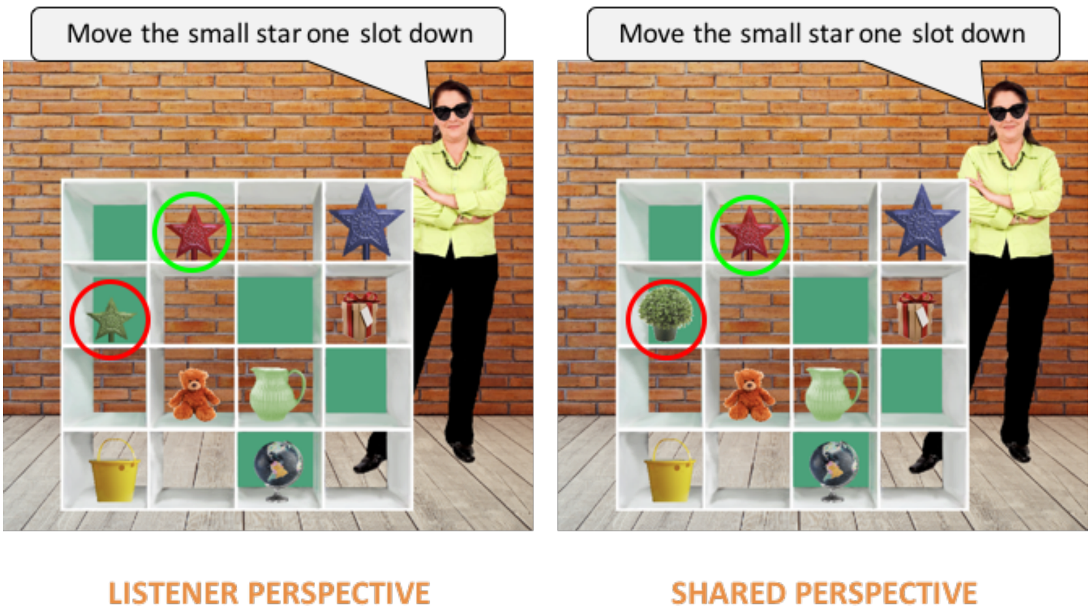


Figure 2: Example stimuli used in the Interactive reference assignment task, showing Listener perspective and Shared perspective conditions.

Inverse efficiency (i.e. reaction time divided by proportion correct) was used as the dependent variable, and was analysed using a mixed ANOVA that crossed the between-subjects factor Age Group (adolescents *vs.* young adults *vs.* older adults) with the within-subjects factor Condition (listener perspective *vs.* shared perspective). We predicted that the inverse efficiency score would be smaller on shared trials compared to listener only trials, reflecting better performance when perspectives were shared. Regarding age effects, we predicted that adolescents and older adults would show greater disruption on listener only trials (i.e. a greater difference in inverse efficiency scores between shared and listener conditions) compared to young adults, due to the cognitive effort required to resolve the discrepancy between self and other viewpoints. We also expected inverse efficiency scores to differ across the age groups (adolescents > young adults < older adults), reflecting processing speed differences.

2.3 Measures of Executive Functioning

2.3.1 Working Memory

Working memory capacity was measured using the Operation-Span task (OSpan; Unsworth, Heitz, Schrock, & Engle, 2005) because it requires individuals to simultaneously store and mentally process information (as in fast-paced social exchanges). Participants were asked to remember a sequence of letters that appeared one at a time on the computer screen (F, H, J, K, L, N, P, Q, R, S, T, and Y); an arithmetical problem served as a distractor between each letter. At the end of each trial, participants were asked to recall the letters in the correct order, by selecting the appropriate letter(s) presented in a 4x3 matrix. The main task consisted of three trials for each of 2 to 7 letter spans (in a randomised order for each participant). This created a total of 18 trials with 81 maths problems and 81 letters. The dependent variable for this task was the Partial Ospan Score, calculated as the total number of letters correctly recalled, regardless of order.

2.3.2 Inhibitory Control

A go/no-go (Lustig, 2001) task was used as a measure of inhibitory control because it assesses individuals' ability to ignore irrelevant information and withhold an inappropriate response (mirroring the need to manage self or other relevant information). Individual letters (21 consonants) were presented in the centre of the screen, in black ink on a grey background. The task included two experimental blocks. In the first block, participants were instructed to press the left arow when an X appeared on the screen (160 go trials) and to press the right arrow to any other letter (40 no-go trials). In the second block, participants were instructed to press the right arrow when an X appeared on the screen (40 no-go trials) and to press the left arrow to any other letter (160 go trials). The dependent variable was accuracy, calculated as % correct responses to go and no-go trials, averaged over both experimental blocks.

2.3.3 Cognitive Flexibility

Cognitive flexibility was measured using the Wisconsin Card Sorting Task (WCST; Grant & Berg, 1948; Miyake et al., 2000) because it provides a reliable test of individuals' ability to shift cognitive strategies in response to changing environmental contingencies (reflecting self- and other-focused strategies). Participants were asked to sort cards according to one of three classification rules: colour (red, blue, yellow, or green), shape (crosses, circles, triangles, or stars), or number of symbols (one, two, three, or four). A series of four cards appeared on the top of the screen which differed in colour, shape, or number of symbols, and one card appeared at the centre bottom. Participants had to figure out which of the three possible sorting rules to adopt according to the feedback that they received after choosing a card; the sorting rule changed throughout the task. The experimental block consisted of 128 cards. The dependent variable was the total number of perseverative errors, defined as the number of times in which participants persisted with an incorrect sorting rule.

2.4. Procedure

Participants completed all tasks in a single testing session in a quiet laboratory at the University of Kent. The order of tasks was counterbalanced across participants, and was run as part of a larger task battery. The entire testing session lasted approximately 3 hours, including breaks when needed.

3. Results

The full datasets and analysis scripts are available on the Open Science Framework web pages (osf.io/9rnxq).

3.1. Hierarchy of social inferences

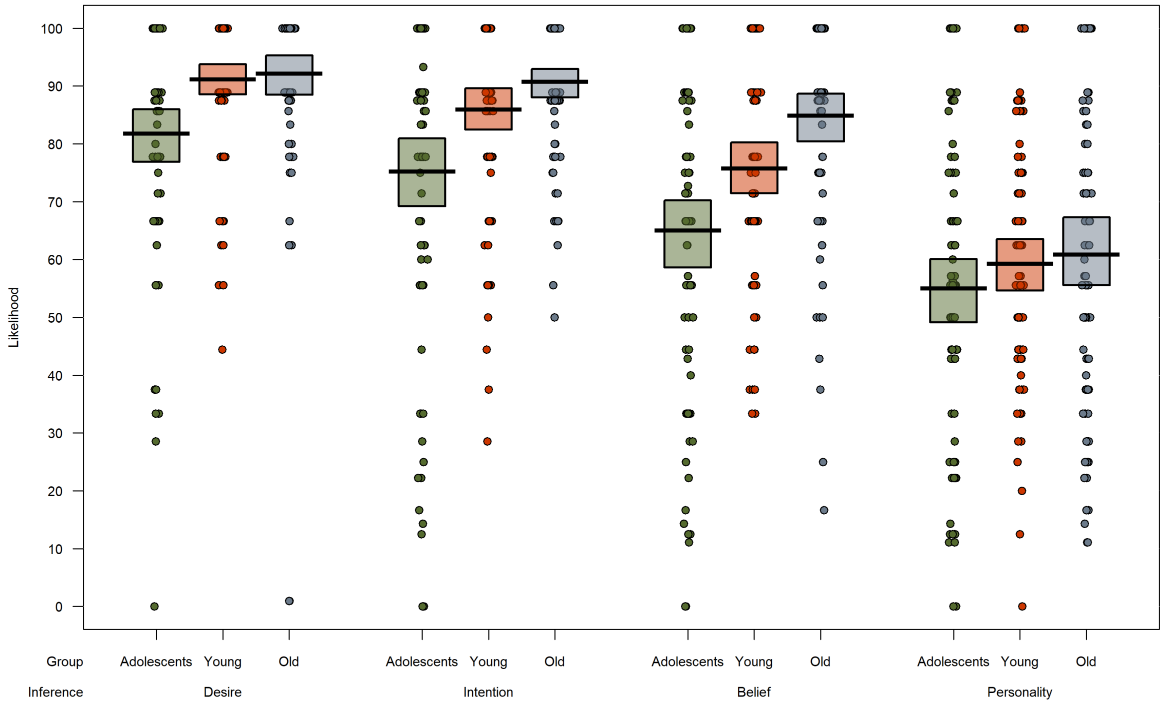
Figure 3 shows the average likelihood of making a correct social inference for each social inference type and age group. A 3 x 4 mixed design ANOVA was used to analyse the data, crossing the between-subjects variable Age Group (adolescents *vs.* young adults *vs.* older adults) with the within-subjects variable Inference (Intention, Desire, Belief, Personality). Full statistical effects are reported in Table 4 (see Supplementary Materials for additional analyses of reaction times).

Table 4: Statistical effects for Likelihood in the Hierarchy of social inferences task. Asterisks show significance of effects, where * $p < .05$; *** $p < .001$.

	df	*F*	*p*	η_p^2
Age Group	(2, 260)	15.78	< .001***	.11
Inference	(3, 780)	159.83	< .001***	.38
Age Group x Inference	(6, 780)	3.06	.006**	.02

Analysis of likelihood revealed significant main effects for both variables. The main effect of Age Group showed that overall, adolescents (M = 69%) were less likely to make correct social inferences compared to young adults (M = 78%; $t(173) = 3.43$, $p < .001$, d = .52), but older adults were more likely make correct social inferences (M = 82%) compared to young adults ($t(174) = 2.23$, $p = .03$, $d = .37$). The main effect of Inference reflected a comparable hierarchy of social inferences to that described by Malle and Holbrook (2012): participants were more likely to more likely to infer a desire (M = 88%), followed by an intention (M = 84%), a belief (M = 75%) and finally personality (M = 58%; all contrasts $p <$ .004).

The Age Group x Inference interaction was also significant. Contrasts between inference types revealed the same significant patterns for all age groups (all contrasts, $p <$ .002, except when comparing intentions and desires in the old group, $p = .50$), which suggests that the basic hierarchy of social inferences does not change with age. Further analyses revealed that Age Group modulated the likelihood of making inferences about the main character's intentions, $F(2, 260) = 14.79$, $p < .001$, $\eta_p^2 = .10$, desires, $F(2, 260) = 8.93$, $p <$ .001, $\eta_p^2 = .06$, and beliefs, $F(2, 260) = 17.19$, $p < .001$, $\eta_p^2 = .12$, but not inferences about personality, $F(2, 260) = 1.28$, $p = .28$. Comparisons between age groups revealed that adolescents were less likely than young adults to infer social behaviour in the videos [intentions, $t(173) = 3.21$, $p = .002$, d = .48; desires, $t(173) = 3.37$, $p < .001$, d = .51; beliefs, $t(173) = 2.94$, $p = .004$, d = .46], but older adults were more likely than young adults to infer intentions, $t(174) = 2.20$, $p = .03$, d = .33, and beliefs, $t(174) = 3.08$, $p = .002$, d = .46.



<u>Figure 3</u>: The likelihood of correctly making social inferences in each age group in the Hierarchy of social inferences task. The plots show raw data points, a horizontal line reflecting the condition mean, and a rectangle representing the 95% Bayesian highest density interval.

3.2. VSPT

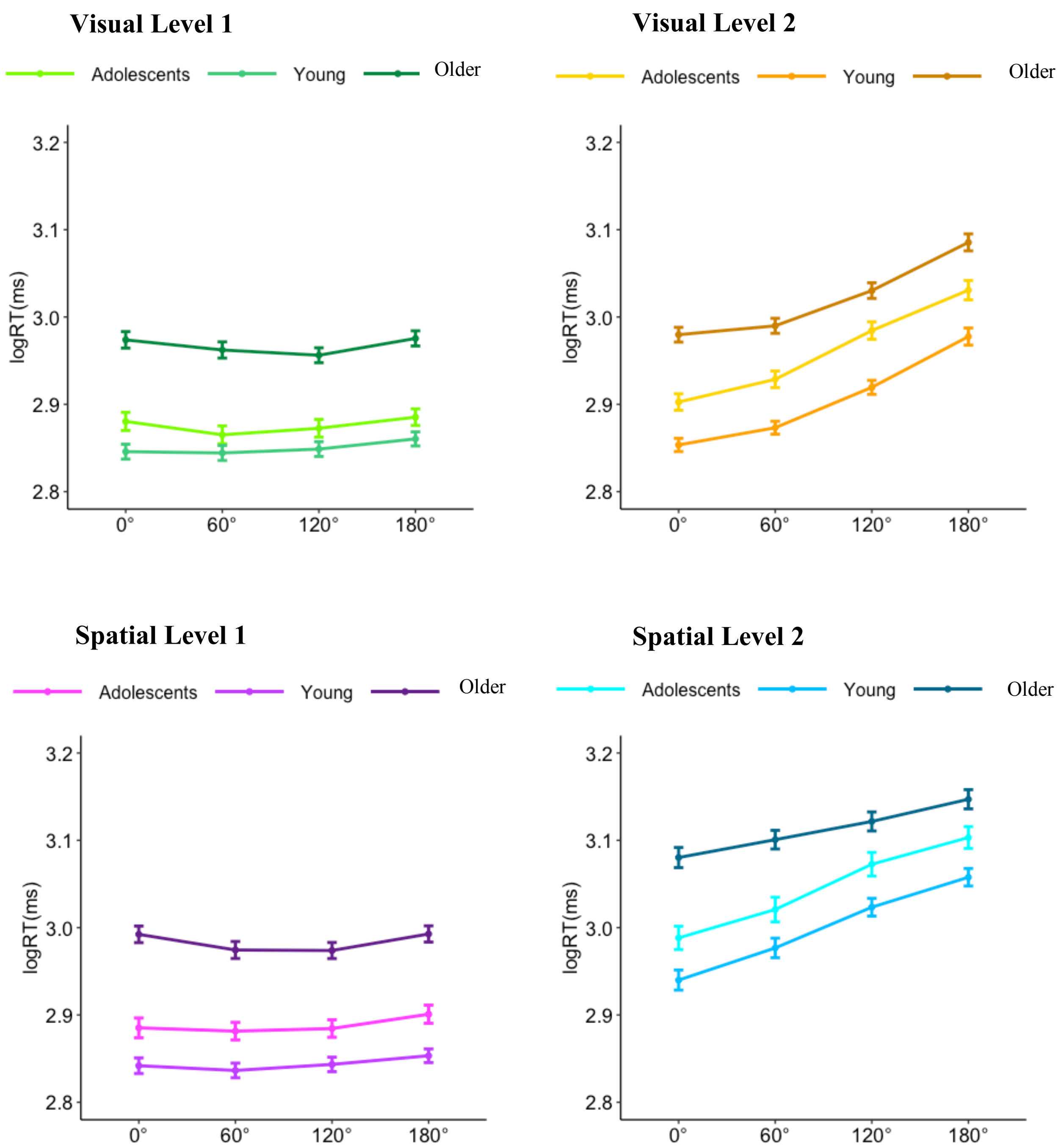
As in Surtees et al. (2013a), reaction times were calculated only on correct trials. Outliers were excluded from the analysis of reaction times if they fell more than 2.5 standard deviations from the age group's mean response time. Figure 4 shows the average log reaction time for each condition and age group. A 3 x 4 x 2 x 2 mixed design ANOVA was used for analysis of log-transformed reaction time data, crossing the between-subjects variable age

Group (adolescents *vs.* young adults *vs.* older adults), with within-subjects variables Angle (0°, 60°, 120°, 180°), Level (1, 2) and Content (Visual, Spatial). Full statistical effects are reported in Table 5, however in the text we limit our reporting to effects that involved age group (see Supplementary Materials for a description of all significant effects).

Table 5: Statistical effects for reaction times in the visuo-spatial perspective-taking task. Asterisks show significance of effects, where * $p < .05$; *** $p < .001$.

	Df	*F*	*p*	η_p^2
Age Group	(2, 260)	69.42	< .001***	.35
Content	(1, 260)	184.23	< .001***	.42
Angle	(3, 780)	380.44	< .001***	.59
Level	(1, 260)	638.52	< .001***	.71
Age Group x Content	(2, 260)	0.97	.38	< .01
Age Group x Angle	(6, 780)	7.62	< .001***	.06
Age Group x Level	(2, 260)	4.20	.02*	.03
Content x Angle	(3, 780)	8.22	< .001***	.03
Content x Level	(1, 260)	123.37	< .001***	.32
Angle x Level	(3, 780)	267.70	< .001***	.51
Age Group x Content x Angle	(6, 780)	1.85	.09	.01
Age Group x Content x Level	(2, 260)	1.76	.17	.02
Age Group x Angle x Level	(6, 780)	2.06	.06	.02
Content x Angle x Level	(3, 780)	8.96	< .001***	.03
Age Group x Content x Angle x Level	(6, 780)	1.25	.28	.01

Analyses revealed that Age Group significantly modulated the effects of Level and Angle, but the 3-way interaction between Age Group, Level and Angle did not reach significance (p = .056). Follow-up analyses for the Age Group x Level interaction showed that while all age groups showed slower responses for level 2 *versus* level 1 perspective-taking (M_{level1} = 1.90ms^{log} *vs.* M_{level2} = 2.00ms^{log}; all ts > 12, ps < .001), this difference was significantly smaller in the older adults (M_{diff} = 0.09ms^{log}) compared to both adolescents (M_{diff} = 0.12ms^{log}; t(173) = 2.72, p = .007, d = .40) and young adults (M_{diff} = 0.11ms^{log}; t(174) = 2.20, p = .03, d = .19). Follow-up analyses for the Age Group x Angle interaction showed that the effect of angle was significant in all three age groups (all Fs > 90, ps < .001), but the reaction time increase from 0° to 180° angle was greater among young adults compared to both adolescents (t(173) = 3.80, p < .001, d = .55) and older adults (t(174) = 4.42, p < .001, d = .60).



<u>Figure 4</u>: Log reaction times in each condition and age group in the visuo-spatial perspective-taking task, showing the condition mean and standard errors.

3.3. Interactive reference assignment

Only experimental trials were included in our analyses. Accuracy was calculated as the proportion of trials on which participants correctly selected the target object, and reaction times were calculated only on correct trials. Outliers were excluded from reaction times if they fell more than 2.5 standard deviations from the age group's mean response time or were faster than 200ms (since this indicated they selected the object before hearing the scalar contrast term). We then calculated a composite measure of inverse efficiency by dividing participants' average reaction time by the proportion correct on a given condition.

Figure 5 shows the average inverse efficiency score for each condition and age group. A 3 x 2 mixed design ANOVA was used for analysis, crossing the between-subjects factor Age Group (adolescents *vs.* young adults *vs.* older adults) with the within-subjects factor Condition (listener only *vs.* shared view). Full statistical effects are reported in Table 6 (see Supplementary Materials for separate analyses of accuracy and reaction time data).

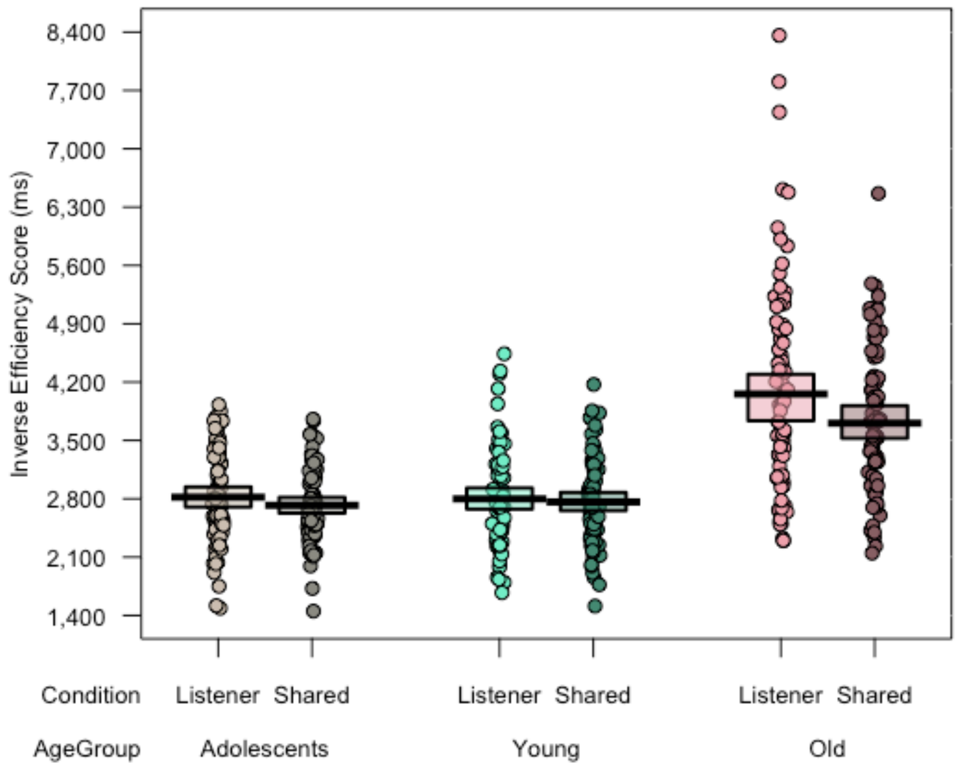
Table 6: Statistical effects for inverse efficiency in the interactive reference assignment task. Asterisks show significance of effects, where ** $p < .01$, *** $p < .001$.

	df	*F*	*p*	η_p^2
Age Group	(2, 260)	23.80	< .001***	.16
Condition	(1, 260)	9.51	.002**	.04
Age Group x Condition	(2, 260)	5.60	.004**	.04

Analysis revealed a significant main effect of Age and Condition. The main effect of Age Group showed that overall, young adults (M = 2,810ms) performed better in selecting the target object (i.e. had a shorter inverse efficiency score) compared to older adults (M = 4,581ms; $t(350) = 5.09$, $p < .001$, $d = .54$), but did not differ compared to adolescents (M =

2,861, *t*(340) = .57, *p* = .56, *d* = .06). The main effect of Condition showed that participants performed worse in the listener only condition (*M* = 3,774ms) compared to the shared view condition (*M* = 3,065ms).

The Age Group x Condition interaction was also significant. Follow-up analyses revealed that while the adolescent (*t*(86) = 2.17, *p* = .033, *d* = .19) and older (*t*(87) = 2.66, *p* = .009, *d* = .39) age groups performed significantly worse in the listener only condition than the shared view condition, young adults did not show a performance difference between the two perspective conditions, *t*(87) = 1.31, *p* = .19, *d* = .15.



<u>Figure 5:</u> Inverse efficiency score in each condition and age group in the interactive reference assignment task. The plots show raw data points, a horizontal line reflecting the condition mean, and a rectangle representing the 95% Bayesian highest density interval.

3.4 Correlation analyses

A series of correlations examined relations between performance on the three measures of perspective-taking, three measures of EF, and age (see Table 7). Correlations were conducted separately to examine development from adolescence to young adulthood (i.e. age 10-40 years old) and decline from young adulthood to older age (i.e. 20-80 years old), since these relationships are not linear across the lifespan, with cognitive decline beginning around 40 years old (Ferguson et al., 2021). Age was entered as a continuous variable in each model, alongside the relevant perspective-taking measure(s) for each task and the three EFs (working memory capacity, inhibitory control and cognitive flexibility). The outcome measure in the hierarchy of social inferences task was the likelihood of correctly making a social inference (averaged across the four inference types), in the visuo-spatial perspective-taking task it was log reaction times for level 1 and 2 judgements (averaged over visual/spatial content and the four angles of rotation)[1], and in the interactive reference assignment task it was the inverse efficiency score (i.e. reaction time/accuracy) in the Listener condition.

Results showed that from adolescence to young adulthood, age was significantly correlated with performance on the hierarchy of social inferences task (i.e. the likelihood of making social inferences increased with age), visuo-spatial level 1 and 2 perspective-taking (i.e. decreasing response times with advancing age), inhibitory control (i.e. increasing go/no-go accuracy with advancing age) and cognitive flexibility (i.e. reducing number of perseverative errors with advancing age). Performance on all four perspective-taking measures was significantly related to individual differences in all three EFs (i.e. increasing EF ability was associated with improved perspective-taking). In addition, the three EF

[1] The choice of outcome variable in the VSPT task was informed by our prediction that level 2 perspective-taking would be more susceptible to age-related difficulties than level 1 perspective-taking.

measures correlated with each other, and visuo-spatial level 1 and 2 perspective-taking correlated with each other and both other perspective-taking tasks in these age groups.

From young to older adulthood, age was significantly correlated with performance on all measures of perspective-taking as well as working memory and cognitive flexibility[2], reflecting an increased likelihood of making social inferences with advancing age, but declining performance on all other measures with advancing age. Individual differences in EFs were not associated with the likelihood of making a social inference or interactive reference assignment, but working memory and cognitive flexibility were correlated with visuo-spatial level 1 and 2 perspective-taking. In these age groups, cognitive flexibility correlated with working memory and inhibitory control, and again visuo-spatial level 1 and 2 perspective-taking correlated with each other and both other perspective-taking tasks.

Table 7: Correlation matrix illustrating the relationships between age, performance on the three measures of perspective-taking, three measures of executive function, and age. Asterisks indicate a significant correlation (* $p < .05$, ** $p < .01$, *** $p < .001$), and the cell values show *r*.

	2.	3.	4.	5.	6.	7.	8.
Adolescence to Young adulthood (N=175)							
1. Age	.34***	-.25***	-.27***	-.11	.09	.49***	-.39***
2. Social inferences		-.32***	-.25***	-.01	.22**	.17*	-.21**
3. VSPT Level 1			.66***	.27***	.30***	-.30***	.32***
4. VSPT Level 2				.17*	.19**	.22**	.21**
5. Reference assignment					-.33***	-.21**	.26***

[2] The absence of a decline in inhibitory control in older age is consistent with previous studies that have used the go/no-go task and found that older adults adopt a more conservative response strategy by spending more time to respond to minimise the rate of errors (see recent meta-analysis Cheng, Tasi, & Cheng, 2019).

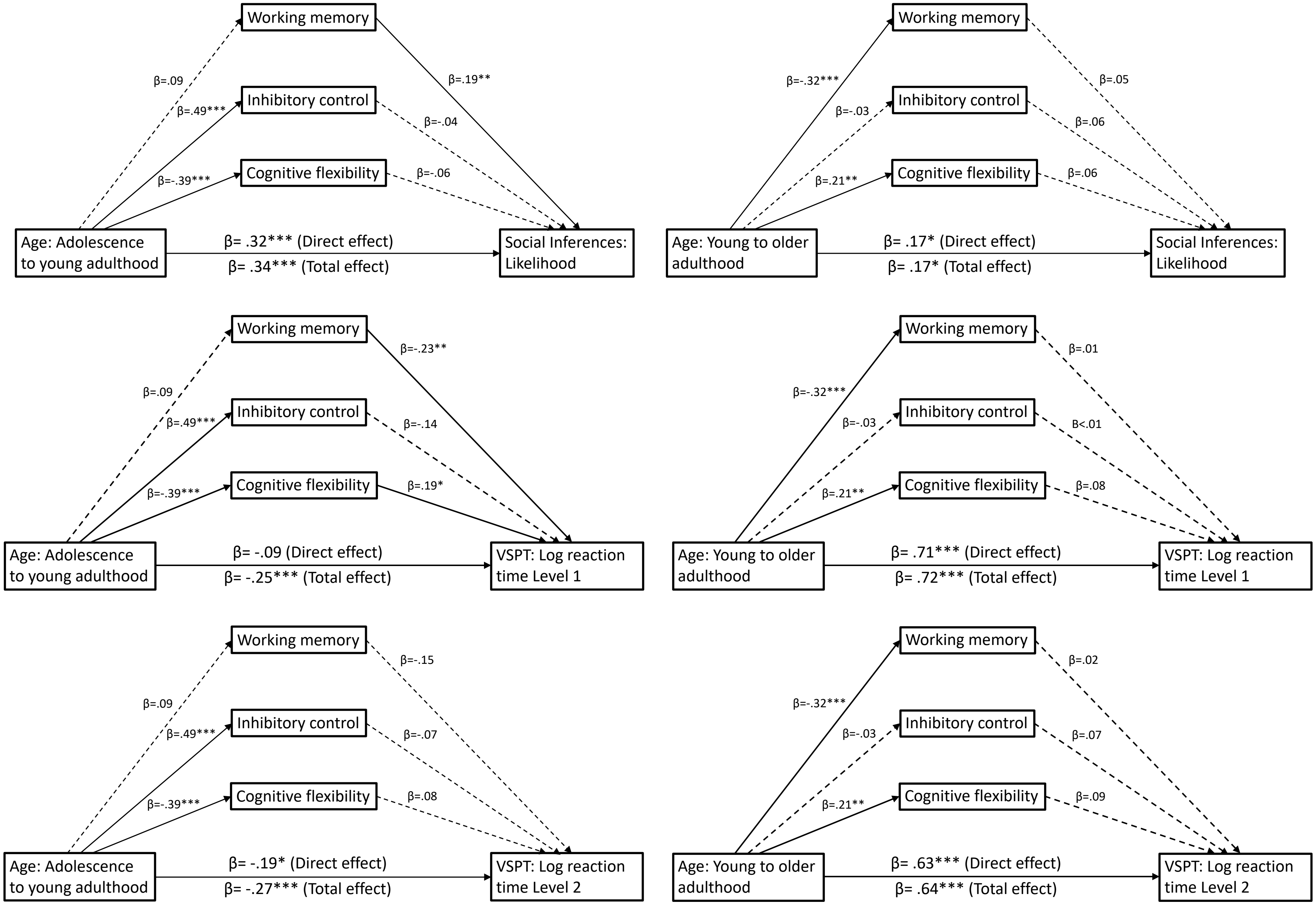
6. Working memory						.20**	-.19**
7. Inhibitory control							-.36***
8. Cognitive flexibility							
Young adulthood to Older adulthood (N=176)							
1. Age	.17*	.72***	.64*	.28***	-.32***	-.03	.21**
2. Social inferences		.06	.14	.15	-.01	.05	.08
3. VSPT Level 1			.76***	.28***	-.19**	.03	.20**
4. VSPT Level 2				.33***	-.20**	-.13	.22**
5. Reference assignment					-.04	.02	.05
6. Working memory						.12	-.20**
7. Inhibitory control							-.25***
8. Cognitive flexibility							

3.5 Mediation analyses

To examine the extent to which age-related changes in EFs influence the relationship between age and perspective-taking, we conducted a series of multiple mediation analyses. Analyses were conducted separately to examine development from adolescence to young adulthood (i.e. age 10-40 years old) and decline from young adulthood to older age (i.e. 20-80 years old). As illustrated in Figure 6, each model included age (as a continuous variable) as the predictor, the three EFs (working memory capacity, inhibitory control and cognitive flexibility) as the mediators, and the relevant perspective-taking measure(s) for each task as the outcome (as detailed for the correlations above). These mediation models provide information about the direct effect of age on each perspective-taking measure (i.e. controlling for changes in EFs), the indirect effect of age on each perspective-taking measure via each EF (i.e. controlling for direct effects of age on perspective-taking, and effects of other EFs), and the total effect of age and the combined EFs on each perspective-taking measure. Analyses were conducted in SPSS, using the PROCESS macro (model 4, Hayes, 2013), with 95% bootstrap confidence intervals for the indirect effect involving 5,000 repetitions. We report the standardized coefficients for each path due to the different units across our measures.

Replicating the patterns reported in the main analyses and correlations above, between adolescence and young adulthood, age was directly related to performance on the hierarchy of social inferences task (i.e. the likelihood of making social inferences increased with age), visuo-spatial level 2 perspective-taking (i.e. decreasing response times with advancing age), inhibitory control (i.e. increasing go/no-go accuracy with advancing age) and cognitive flexibility (i.e. reducing number of perseverative errors with advancing age), but not visuo-spatial level 1 perspective-taking interactive reference assignment or working memory. In these age groups, the likelihood of making a social inference was significantly predicted by individual differences in working memory, level 1 perspective-taking was predicted by working memory and cognitive flexibility, and the listener inverse efficiency score was predicted by both working memory and cognitive flexibility; none of the other models showed a significant predictive relationship between EFs and the outcome measure. Interestingly, while the direct effect of age was not significant for level 1 perspective-taking, the total model was significant, showing that the combined effects of age and EFs predicted level 1 perspective-taking; the indirect effect via cognitive flexibility ($\beta = -.07$, 95% CIs -.14 to -.02) mediated age-related changes on this measure. The indirect effects were non-significant on all other models, which suggests that the combined EFs contribute to but do not mediate the effect of age on developing perspective-taking ability on these measures.

Between young and older adulthood, age had a significant direct predictive effect on all measures of perspective-taking, reflecting an increase in likelihood of making social inferences in older age, but a performance decline on the visuo-spatial perspective-taking and interactive reference assignment tasks with advancing age. In addition, age predicted working memory and cognitive flexibility, reflecting the expected declines in these EFs with advancing age. None of models showed a significant predictive relationship between the EFs and any of the perspective-taking outcome measures, and none of the indirect effects were significant. This pattern suggests that while advancing age is related to broad declines in perspective-taking ability, these changes cannot be attributed to age-related changes in EFs.


Working memory
Inhibitory control
Cognitive flexibility
β=.09
β=.49***
β=-.39***
β=.19**
β=-.04
β=-.06
Age: Adolescence to young adulthood
β= .32*** (Direct effect)
β= .34*** (Total effect)
Social Inferences: Likelihood
Working memory
Inhibitory control
Cognitive flexibility
β=-.32***
β=-.03
β=.21**
β=.05
β=.06
β=.06
Age: Young to older adulthood
β= .17* (Direct effect)
β= .17* (Total effect)
Social Inferences: Likelihood
Working memory
Inhibitory control
Cognitive flexibility
β=.09
β=.49***
β=-.39***
β=-.23**
β=-.14
β=.19*
Age: Adolescence to young adulthood
β= -.09 (Direct effect)
β= -.25*** (Total effect)
VSPT: Log reaction time Level 1
Working memory
Inhibitory control
Cognitive flexibility
β=-.32***
β=-.03
β=.21**
β=.01
B<.01
β=.08
Age: Young to older adulthood
β= .71*** (Direct effect)
β= .72*** (Total effect)
VSPT: Log reaction time Level 1
Working memory
Inhibitory control
Cognitive flexibility
β=.09
β=.49***
β=-.39***
β=-.15
β=-.07
β=.08
Age: Adolescence to young adulthood
β= -.19* (Direct effect)
β= -.27*** (Total effect)
VSPT: Log reaction time Level 2
Working memory
Inhibitory control
Cognitive flexibility
β=-.32***
β=-.03
β=.21**
β=.02
β=.07
β=.09
Age: Young to older adulthood
β= .63*** (Direct effect)
β= .64*** (Total effect)
VSPT: Log reaction time Level 2

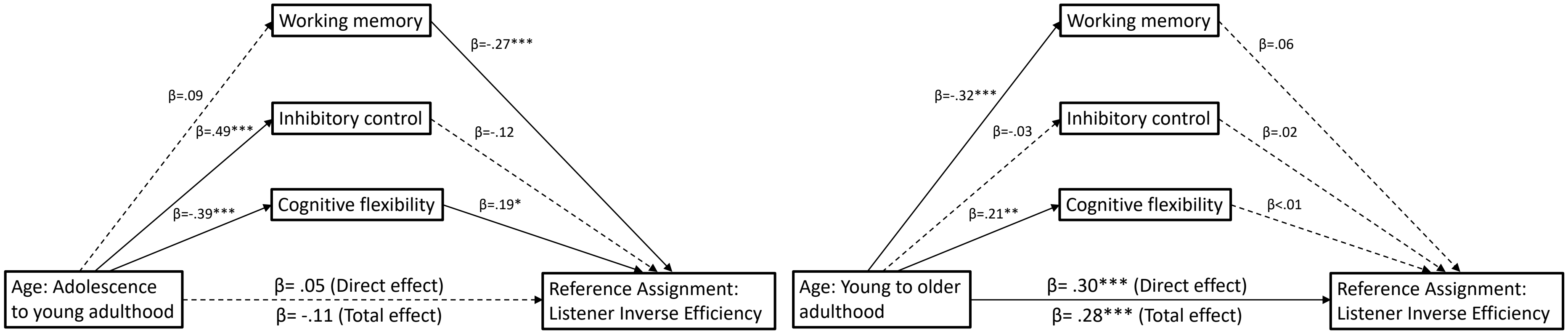


Figure 6: Multiple mediation models, separately for development (i.e. adolescence to young adulthood; left panels) and decline (i.e. young to older adulthood; right panels), with age (as a continuous variable) as the predictor, the three EFs (working memory capacity, inhibitory control and cognitive flexibility) as the mediators, and the relevant perspective-taking measure(s) for each task as the outcome. Note that ß reports the standardized coefficient for each path. Mediation models show the direct effect of age on each perspective-taking measure (i.e. controlling for changes in EFs) and the total effect of age and the combined EFs on each perspective-taking measure.

3 Discussion

A growing body of research has examined how social cognitive skills develop across the lifespan. This previous research has shown that the ability to take another person's perspective and make inferences about their mental states develops throughout childhood and adolescence (Choudhury et al., 2006; Dumontheil et al., 2010; Symeonidou et al., 2016), and declines in older age (Henry et al., 2013; Mattan et al., 2017; Martin et al., 2019). However, it is unclear whether these changes are universal across all components of social cognition, especially those that involve more spontaneous perspective-taking. Recent accounts of mentalizing have proposed that cognitive mechanisms mediate successful social interaction during cognitively demanding tasks (i.e. those that place high demands on executive functions or language), but that more spontaneous and cognitively efficient mentalizing skills may operate independently of cognitive abilities (Apperly & Butterfill, 2009; Apperly, 2009; Carruthers, 2016). In this paper we tested these predictions by examining the development of perspective-taking from adolescence to young and older adulthood, using three tasks that tapped distinct components of perspective-taking and made different demands on cognitive resources. In addition, we assessed the degree to which age-related changes in the different sub-components of perspective-taking could be predicted by EF skills (working memory, inhibitory control and cognitive flexibility). We predicted that sub-components of perspective-taking that rely on more cognitively effortful mechanisms (i.e. level 2 visual perspective-taking and using a speaker's perspective to infer their referential meaning) would be impaired among adolescents and older adults relative to young adults, but that cognitively efficient processes (i.e. making social inferences and level 1 visual perspective-taking) would not be subject to age-related change.

Overall, older adults showed expected slower response times compared to the two younger groups. In the VSPT task older adults were slower to judge *where* an object was placed relative to an avatar or *what* an avatar could or could not see on an object, and in the referential communication task older adults had larger inverse efficiency scores to select the target object (reflecting slower responding and higher error rates). These results reflect a general cognitive slowing that has been shown in many previous aging investigations (Salthouse et al., 2000; Verhaeghen, 2011). However, each task also revealed interactions between age group and condition effects, which suggests that some of the underlying socio-cognitive processes changed with age.

Results from the social inferences task showed that the basic hierarchy of making mental state inferences was comparable across the lifespan (i.e. the pattern of likelihood between the four different mental states was comparable across age groups). Replicating Malle and Hollbrook (2012), all age groups showed that inferences about desires and intentions were the most likely to be correctly detected, which suggests that they might be activated automatically and reflect more basic aspects of social understanding. In contrast, inferences about others' beliefs were less likely to be detected, possibly due to the difficulty of adjusting from one's own beliefs (Apperly et al., 2008; Epley et al., 2004a). Personality traits were the least likely to be detected, likely because observers need to refer to more information to identify personality traits (Buss & Craik, 1983; Wright & Mischel, 1987). Across all age groups, participants showed a relatively high likelihood of detecting mental states in the videos (~78% of the time), which demonstrates the human ability to mentalize with other people.

Despite showing comparable hierarchies between the different social inferences across the lifespan, the overall likelihood of detecting social inferences increased linearly from adolescence to young adulthood and older adulthood, and differed between the different mental state types (evidenced by the groups x inference interaction). This pattern of age-related change (i.e. increasing likelihood of inferring a mental state with increasing age) was observed for inferences about goals (desires) and intentions, which are thought to be activated relatively automatically and effortlessly, as well as for beliefs, which are more cognitively effortful; no age difference was found for judgements about personality. This shows that there are age differences in the relative ease of carrying out the different types of social inference, even if the basic hierarchy of difficulty is the same across age groups. It is important to note that in our study we checked the accuracy of descriptions when a social inference was detected and only included correct inferences in analyses, so it is unlikely that the increased detection of social inferences among older adults reflects a response bias that might mask some difficulties distinguishing between mental states (as seen in Lecce et al., 2019).

On one hand, these findings of preserved or even enhanced likelihood of making social inferences in older adults contrasts with previous studies that have shown impaired mental state detection in this age group (Bailey & Henry, 2008; Henry et al., 2013; Cavallini et al., 2013), and explicit difficulties in using these mental states to predict others' actions in more cognitively demanding tasks (e.g. Bernstein et al., 2011; Phillips et al., 2011). However, it is possible that they reflect accumulating experience in social situations over the lifespan, which facilitates older adults' ability to make social inferences in the type of everyday scenarios used in the current study (Hess et al., 2005; Leclerc & Hess, 2007). This finding is also consistent with our prediction that social inferences can be activated relatively spontaneously, without a great deal of cognitive effort (as in Ferguson et al., 2015), and therefore are not impaired among adolescents or in older age whose EF capacities are lower. In line with this, our correlation and mediation analyses revealed that none of the EFs were associated with the improvement in likelihood of making social inferences from young to older adulthood, and although all three EFs correlated with enhanced social inference performance between adolescence and young adulthood, none of these EFs mediated the developing ability to make social inferences. Thus, the evidence presented here suggests that the ability to make basic social inferences about others is relatively cognitively effortless (*using* this social inference to predict others' behaviour is likely to be more challenging; Ferguson et al., 2015), and benefits from an accumulation of social experience across the lifespan, meaning that it is protected from age-related decline in older age.

Results from the VSPT task provided further evidence for age-related changes in perspective-taking. Overall, effects replicated previous work in showing that the type of perspective-taking (i.e. level 1 *vs.* level 2) plays a greater role in perspective-taking success than the content (i.e. visual *vs.* spatial); reaction times showed a steeper increase as angle increased for level 2 than level 1 judgements (as in Surtees et al., 2013a). Importantly, age modulated the effects of level and angle, separately. Contrary to our predictions, older adults showed a smaller difference in response times for level 2 *versus* level 1 perspective-taking compared to adolescents and young adults. In addition, adolescents and older adults showed smaller increments in reaction times with increasing angles compared to young adults; this age effect on angle did not differ between level 1 and level 2 judgements. In both cases, the data suggest that the smaller/shallower effects of level and angle seen in older adults is due longer response times on the 'easier' conditions, meaning that older adults experienced increased difficulty in judging the object from the avatar's perspective, even when the perspective shift from self to other was smaller and that other person's perspective has been made salient by the task demands (see Del Sette, Bindemann, & Ferguson, 2022). Thus, while all age groups experienced difficulty judging level 2 perspectives and at larger angles of rotation, older adults continued to struggle even for less cognitively demanding level 1 judgements and with no/small angles of rotation. These age-related difficulties in perspective-taking might also reflect age-related difficulties with mental rotation, since previous studies have highlighted that older adults have an impaired human body rotation (Costello & Bloesch, 2017; Devlin & Wilson, 2010; Martin et al., 2019), therefore future studies should aim to control for these difficulties.

Age effects on the computation of the avatar's perspective were also evident in the correlation and mediation analyses for the VSPT task. Age correlated with level 1 and 2 perspective-taking ability during both development (adolescence-young adulthood) and decline (young-older adulthood) phases. In the mediation models, age had a direct effect on level 1 decline and level 2 development and decline, but did not directly influence the development of level 1 perspective-taking. All three EFs correlated with the development of level 1 and 2 perspective-taking ability from adolescence, and both working memory and cognitive flexibility correlated with the decline of this ability into older age. However, while level 1 development from adolescence to young adulthood was mediated by indirect effects of age-related changes in cognitive flexibility, none of the EFs mediated an indirect effect on level 1 decline or level 2 development and decline. These findings show that some aspects of perspective-taking (i.e. level 1 judgements of what someone else can see) reach maturity early in development (i.e. before adolescence); cognitive flexibility mediated the development of level 1 perspective-taking, and working memory was directly linked to level 1 perspective-taking, thus the development of cognitive resources during adolescence plays an important role in computing *what* another person sees. In contrast, age-related declines in level 1 perspective-taking and development and decline in level 2 perspective-taking could not be clearly linked to age-related changes in EF capacities. This suggests that age-related changes in computing *what* or *how* another person sees something are attributable primarily to social-specific changes, in addition to global changes in a shared network of domain-general processes that support social interaction (e.g. Apperly & Butterfill, 2009; Apperly, 2009; Carruthers, 2016).

Results from the interactive reference assignment task showed that participants had longer inverse efficiency scores (i.e. reflecting longer response times and increased errors) to select the target object when a competitor object was available in privileged view (i.e. listener only condition) compared to when no hidden competitor was available (i.e. shared view condition). This confirmed that participants of all ages experienced egocentric interference when taking another person's perspective (Epley et al., 2004a). Importantly, young adults outperformed both adolescents and older adults. Young adults did not show a performance impairment in the listener condition relative to the shared condition, as seen in the adolescents and older adults; adolescents and older adults experienced greater interference from their own privileged view compared to young adults. These age-related changes were expected in this task since it places high demands on EFs and language, and requires participants to infer, store and use information about another person's perspective (Ferguson et al., 2015). The changes reflect an extended period of social cognitive development in adolescence and a decline in older age (Blakemore & Choudhury, 2006; Dumontheil et al., 2010; Mattan et al., 2017), and key periods of change in cognitive abilities (including language and inhibitory control; Diamond, 2002; Salthouse, 2009).

In this interactive reference assignment task, correlation and mediation analyses revealed distinct effects during development from adolescence and decline into older age, which suggests that different mechanisms may be involved at different stages of the lifespan. Age was not directly related to listener inverse efficiency scores from adolescence to young adulthood, suggesting that the ability to manage the egocentric perspective is relatively stable across these younger ages, but was directly related to listener inverse efficiency scores from young to older adulthood, suggesting that this ability undergoes significant decline in older age. Moreover, individual differences in working memory, inhibitory control and cognitive flexibility all correlated with perspective-taking in this interactive reference assignment task among adolescents and young adults, but did not influence perspective-taking performance among young and older adults. This pattern suggests that EFs play a crucial role in managing the early development of perspective-taking in this task, and that even early adolescents can manage the task demands successfully if they have high levels of EF capacity. Later in development, high functioning EF capacities are not sufficient to maintain performance in this task, thus other factors seem to underlie the difficulties that older adults experience in interpreting verbal instructions from another person's perspective and managing the egocentric view. In short, early development of perspective-taking in this interactive reference assignment task seems to rely on EFs, but later decline seems to reflect a specific decline in social ability. Finally, we note that overall participants performed close to ceiling levels on this task (96% accurate overall). Future research could test whether the effect of age and the mediating role of EFs on performance might change if task difficulty was increased further (as in dynamic real-life social interaction), perhaps using a secondary task or more complicated verbal instructions.

Taken together, our data provide support for the selective involvement of social and cognitive processes to support perspective-taking. The findings therefore fit with cognitive theories of mindreading that have proposed that the mentalising system continues to develop throughout our lives, and is influenced by growing social and communicative experience and maturing cognitive and language mechanisms, all of which strengthen the connection between mindreading and cognition (Apperly & Butterfill, 2009, 2011; Apperly, 2009; Carruthers, 2016; Wade et al., 2018). Our data showed that some aspects of social cognition show early development (e.g. level 1 perspective-taking and interactive reference assignment), are spared from age-related decline, and even improve across the lifespan. For example, the ability to make basic social inferences about others advanced from adolescence to older age, suggesting that this ability is relatively cognitively efficient and influenced to a greater extent by accumulating social experience. Other aspects of social cognition show an extended period of development (e.g. level 2 perspective-taking and interactive reference assignment) and steady decline into older age. Individual differences in cognitive abilities contributed to overall performance in these tasks, but could not explain age-related development and decline even in these more cognitively demanding aspects of social cognition, suggesting that a more specific age-related decline in social ability operates independent of these cognitive changes.

Recently, researchers have aimed to identify the neural and computational mechanisms that explain this link between ToM and EFs. In their review of empirical evidence, Wade et al. (2018) found evidence to support a bidirectional link between ToM and EFs, concluding that ToM shares some (but not all) neuroanatomical mechanisms with EFs, and that these mechanisms scaffold and reinforce each other as the brain matures. This suggests that the overlap might become greater throughout the lifespan, and therefore impairments become more evident. Similarly, Weimer et al. (2021) have proposed an integrated transactional framework in which emotional self-regulation (including EFs) interacts with prosocial outcomes via bidirectional feedback loops (i.e. improved self-regulation leads to social interactions that increase opportunities to exercise mentalising, and motivates future prosocial behaviour), and therefore plays a key role in predicting the development of ToM in childhood and adolescence. Further research is required to systematically manipulate the cognitive, social and language constraints on social cognition to identify and test these mechanisms.

This work addresses some of the key limitations from previous work. For instance, the mixed evidence on aging and social interaction could reflect the use of a single task to measure different sub-components of social cognition, with each placing different demands on cognitive resources, and controversy regarding task validity (e.g. Gallant et al., 2020;

Hayward & Homer, 2017; Schaafsma et al., 2015). We used three tasks that each tapped different aspects of perspective-taking, and showed a high degree of correlation between the measures; during development only, social inferences and interactive reference assignment failed to correlate, and during decline in older age ability to make basic social inferences did not relate to any other measure (likely reflecting the unusual pattern of improvement with increasing lifetime experience in this task). Future work should take a more targeted approach to test effects in other sub-domains of social cognition. In addition, the majority of studies in this area have examined social processes in a single age group, and those that have compared across developmental stages have typically been limited by employing different batteries of social tasks for different age groups in order to avoid ceiling effects. Given these methodological problems, it is unknown whether previously reported age-related differences in ToM are limited to a single measure or specific modality, or whether they represent more general aging effects on social cognition. Our studies demonstrate the benefits of adopting multiple tasks to tap different sub-components of social ability, as well as including larger sample sizes that extend beyond a single age group and more representative sample demographics (i.e. broad community recruitment rather than undergraduate student populations).

Nevertheless, one important limitation of this work is that all of our tasks involved an explicit instruction to consider another person's perspective, and as such it is unknown whether there are age differences in the likelihood and timing of social inferences and judgements when these have not been consciously initiated. In addition, all of the tasks required participants to make inferences about the mental states of anonymous others (often even non-real avatars) as a third-party observer; these isolated contexts that do not reflect the complexity and dynamic nature of real-life social interaction. Interactivity is known to alter sensitivity to others' perspectives and influence communication success (Kuhlen & Abdel

Rahman, 2022; Surtees, Apperly, & Samson, 2016). Thus, future research is needed to test the extent to which findings in these controlled contexts truly reflect real-life interaction with co-present others (as in De Lillo et al., 2021), and whether older adults might particularly benefit from these interactive social contexts that motivate them to engage with others more closely (Hess, 2014). It is also important to note that since age effects were examined here by comparing different cohorts of participants rather than by tracking the same individuals across development, it is difficult to attribute group differences precisely to stages of development. A recent model has suggested that 'cognitive gadgets' (including reasoning, using language, and mindreading) are culturally inherited and learned (Heyes, 2018), and as such social abilities change not only over the lifespan, but also vary over social and economic environments, and over different generations. Ultimately, future studies using a long-term longitudinal approach are needed to disentangle the social and cognitive contributions to development.

In conclusion, our results show that different sub-components of social cognition show distinct patterns of change with age. On one hand, some aspects of perspective-taking, such as inferring others' mental states, are not subject to age-related change and in fact improve with age, which suggests that they can be activated relatively rapidly, effortlessly and spontaneously. On the other hand, some components of perspective-taking are subject to developmental changes from adolescence to older age, with performance peaking in young adulthood before a decline into older age. However, while EF capacities showed a high level of association with performance on these tasks (reinforcing the suggestion that they are cognitively effortful), none of the age-related declines in perspective-taking were mediated by age-related changes in EFs. Success in social interaction therefore seems to depend on the degree to which a specific social function places demands on executive function and language, or whether it can be developed through social experience, however maintaining high levels of cognitive functioning in older age is not sufficient to prevent age-related declines in social domains.

Context of the Research

This research was conducted as part of a European Research Council grant, awarded to HJF (Ref: CogSoCoAGE; 636458), on which MDL was a PhD student. The project addressed three main questions: what is the cognitive basis of social communication, how does this change across the life-span, and can training these underlying cognitive skills enhance impaired social skills. The data presented here form part of the time 1 battery of assessments- participants subsequently completed 21 days of training in one of three executive functions (or an active control group) and repeated the battery (time 2 data not discussed in the current paper). The findings link with HJF's broader research program examining the cognitive basis of social communication, and motivates her future plans to study social interaction as a dynamic multi-person communicative event, focusing on the coordination of social interaction cues in older (*vs.* younger) adults, and how this impacts on understanding and memory in different conversational contexts.

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