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Department of Brain and Behavioral Sciences (DBBS)
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Increasingly Coordinated: Propensity for Cooperation and Aversion to Competition in Children, Adolescents and Young Adults

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Contents

Abstract

Adolescence is an age of social re-orientation during which developing socio-cognitive skills allow people to better coordinate their behavior to their social environment, such as to different interaction partners. Little is known, however, about the development of coordination abilities in different strategic environments during this age. To fill this gap, we used game theoretic paradigms to investigate if, during adolescence, people improve in their ability to distinguish between cooperative and competitive environments. N= 596 participants between the ages of 9 and 48, of which 150 children (9–11-year-olds), 147 adolescents (12-15) and 299 adults (18-48), coordinated their choices with an anonymous peer without communicating and without feedback from previous outcomes, thus based only on the commonly visible incentives. Each game involved a series of choices between two options: a low-paying but sure option (e.g., 4 coins), and a potentially high-paying but uncertain option (15 coins or 0). In a cooperative condition, the maximum payoff of 15 was obtained if both players chose the uncertain option; conversely, in the competitive condition, the maximum payoff was obtained only if one player chose the uncertain option and the other did not, and if both players chose the uncertain option both obtained nothing. Finally, in a non-social control condition, the unsure payoff was obtained based on a random lottery draw. Participants of all ages chose the uncertain option more frequently in the cooperative environment relative to competitive one, and this propensity for cooperation increased during adolescence. Adults also showed greater choice variability and longer response times in the competitive condition relative to the cooperative condition. This aversion to competition was not observed in children and was only partly observed in adolescents. Age-related differences in aversion to competition but not propensity for cooperation, were partly explained by age-related improvements in non-verbal reasoning. These findings demonstrate that coordination abilities improve during adolescence and that this is determined by an adolescent developing propensity for cooperation and an adolescent emergent aversion to competition.

Keywords: Adolescence, Coordination, Cooperation, Competition, Strategy

1. Introduction

1.1 Coordination and Socio-Cognitive Development

Coordinating with others is a complex decision-making process which takes place on a larger scale in humans compared to other species (Raihani, 2021) and is considered to be an important evolutionary trait underlying many achievements of humankind (Melis, 2013). In some cases, coordination can involve cooperation, from simple daily displays of kindness or law obedience to larger-scale efforts involving projects such as developing new treatment, starting a workplace union or winning a championship, all of which involve working towards a common goal. In other cases, coordination can involve competition, as it happens when shopping for groceries during early or late hours, in the hope of avoiding the rush.

Coordination involves capabilities which are generally more refined in humans compared to other species, specifically cognitive and social abilities (Herrmann et al., 2007; Langdon, 2022; Tomasello, 2022). To coordinate with others, people need to both understand what the best course of action might be in the given circumstance, and guess what others might do based on previous social interactions and additional beliefs. This requires social and cognitive abilities that undergo gradual improvement and increase in complexity not only during childhood, but also during adolescence (e.g., Beauchamp & Anderson, 2010; Chierchia et al., 2019; Hartung et al., 2020; Symeonidou et al., 2016). Indeed, recent literature has shown that, during adolescence, people become increasingly better at tuning their decision making to the type of person they are interacting, cooperating more with trustworthy vs. untrustworthy interaction partners or friends vs. strangers (Chierchia, Tufano, et al., 2020; Sijtsma et al., 2023; Westhoff et al., 2020). This suggests that, during adolescence, people increasingly use the social context (i.e., information about their interaction partners) to navigate social decision making. However, it is unclear if, during adolescence, people also become better at distinguishing between different strategic contexts requiring coordination, that is, if their strategic ability improves.

In contrast to social contexts that are defined by interaction partners, strategic contexts are defined by the incentives of a social decision-making problem. In some strategic contexts, or, as called in game theory, “games”, the incentives can foster cooperation, in others they can foster competition (C. F. Camerer, 2003; C. F. Camerer & Fehr, 2006). Previous experimental literature has shown that adults efficiently change their decision strategies when passing between cooperative and competitive decision contexts (Chierchia et al., 2018). However, the developmental trajectories of cooperative and competitive coordination abilities are still unknown. During development, when do people begin to distinguish between cooperation and competition, or between games against other people and non-social games?

Considering the strong involvement of social and cognitive factors in coordination, since it entails strategic interactions between individuals, we can look for a possible emergence of coordination abilities during adolescence, where these abilities are becoming increasingly sophisticated. Indeed, adolescence has been recently shifting from being perceived as an age of mostly “storm and stress” (Buchanan & Bruton, 2016; Buchanan & Hughes, 2009) and increased sensation-seeking (Steinberg et al., 2018), to being viewed as a period of protracted neural, and perhaps an even sensitive or critical period (Fuhrmann et al., 2015), for social and cognitive development (Hartung et al., 2020).

1.2 Adolescent Development

1.2.1 Brain Development

Before technological and methodological advancements, it was generally believed that brain development was largely complete by the end of childhood (Konrad et al., 2013; Mason, 2009). However, over twenty years of neuroimaging have led to a revision of this belief. Indeed, although the first years of life are the time wherein changes in the brain are at their fastest rates (Bethlehem et al., 2022), large-scale and cross-cultural studies have shown that adolescence is also a period of marked brain changes (Bethlehem et al., 2022; Mills et al., 2016). This protracted neuroplasticity has been demonstrated with generalized decrease in grey matter volume, increase in white matter volume (Bethlehem et al., 2022; Lebel & Beaulieu, 2011; Mills et al., 2016), protracted myelination (Grydeland et al., 2019), axonal growth (Genc et al., 2023; Paus, 2010), pruning (i.e., gradual elimination of extra synapses and reduction of dendritic density; Santos & Noggle, 2011). From a functional connectivity perspective, instead, we can also find the consolidation of long-range connections and weakening of short-range ones, related perhaps to greater processing efficiency (Ernst et al., 2015).

All the aforementioned brain changes occur in a heterochronic fashion, which means that different areas undergo development at different rates and stages (rather than all changing at the same time), in terms of grey matter thinning (Tamnes et al., 2017), myelinization (related to white matter increase; Grydeland et al., 2019) and pruning (Huttenlocher & Dabholkar, 1997). Furthermore, Grydeland et al. (2019) found a bimodal distribution of peak white matter growth, comprising an early wave of primary sensory and motor cortices increase during childhood, and a post-puberal wave of association, limbic and insular cortices (related to social and cognitive abilities), increasing during late adolescence.

Importantly, several of the age-related changes in brain structure and function have been linked with pubertal hormones, as well as with changes in the environment, which are fairly concentrated during adolescence (Adolescence, 2011; Morningstar et al., 2019). Additionally, several brain measures reach their peak at this age, such as subcortical and total cerebrum volume, but perhaps even more interestingly we can also find a peak in variability towards the end of adolescence in white and subcortical grey matter volume (Bethlehem et al., 2022). This suggests that adolescence is also the age where we find peak individual differences in brain structure, i.e., the moment in our life span when our brains differ between each other.

Ultimately, these findings suggest that brain development is far from concluded by the end of childhood, but instead continues markedly throughout adolescence, further suggesting that this is a sensitive age for cognitive and social development (Bethlehem et al., 2022).

1.2.2 Cognitive Development

The various changes in the brain occur in parallel with the development of cognitive abilities, many of which have been shown to improve linearly or asymptotically (Hartung et al., 2020; Tamnes et al., 2010), and perhaps become increasingly differentiated towards adulthood (Hartung et al., 2020). For example, continued improvement of executive functions (EFs; e.g., updating, inhibition, shifting) have been associated with grey matter thinning of different brain areas during adolescence (Tamnes et al., 2010), and these function-structure associations have sometimes been especially observed in younger people (e.g., younger than 30) compared to adults (Krogsrud et al., 2021). Indeed, the relationship between cognitive abilities and brain changes seems to depend on age, seeing as a study by Wendelken and colleagues (2017) showed that structural connectivity seems to predict changes in reasoning ability only in people younger than 11, while it predicts functional connectivity changes over and above age. In certain cases, brain activity has been shown to better predict performance changes in cognitive tasks rather than structural changes. For example, one study (Dumontheil, Apperly, et al., 2010) showed that age-related improvements in cognitive were related to decreased brain activity, pointing towards an increase in efficiency with age. However, one review by Crone and Dahl (2012) found a mixed picture, with adolescents displaying higher variability of activation depending on the investigated areas. This might suggest higher flexibility in employing executive functions, as well as less automaticity during adolescence compared to later ages.

The aforementioned studies delved into changes in cognitive abilities in relation to age, but did not directly assess improvements in terms of learning capabilities. Indeed, adolescence also represents a period of greater improvement rates following training sessions for certain cognitive skills (e.g., relational reasoning) compared to earlier stages (Knoll et al., 2016), hinting at heightened plasticity during this time. Possibly in support of Hartung and colleagues' findings (2020), these improvements were not the same in magnitude for the various non-verbal reasoning skills trained during the experiment (e.g., improvement in relational reasoning but not as much in face-perception performance), which further suggests increasing differentiation of cognitive abilities as well as sensitivity to train them.

As for cognitive development in general, these findings point to an overall asymptotic/linear increase in executive function and related abilities (Hartung et al., 2020), with less consensus regarding how this development is related to brain changes (Crone & Dahl, 2012; Dumontheil, Hassan, et al., 2010; Krogsrud et al., 2021), although we can argue that such connection between cognitive abilities and neurophysiological changes seems to be fairly noticeable in adolescence. In addition, we can find heightened learning capability for non-verbal reasoning and increased exploratory tendencies when making choices in unfamiliar environments (Chierchia et al., 2023; Knoll et al., 2016).

1.2.3 Social Development

The aforementioned changes in adolescence occur during a period where the amount of time spent interacting with peers increases, along with importance attributed to them, while time spent with parents decreases (Crone & Dahl, 2012). Most likely, those cognitive abilities develop not simply to solve individual problems, but also social ones (Choudhury et al., 2006). That is why, when investigating coordination abilities during adolescence, it is important to consider social cognition (Blakemore & Choudhury, 2006). Indeed, this period sees the improvement of adolescents' social skills as well, not only thanks to neurobiological and cognitive changes, but also because they might need those skills in order to integrate into society and manage new challenges (Alderman et al., 2019; Kelsey & Simons, 2014).

Arguably, one of the most important abilities regarding social cognition is Theory of Mind (ToM), i.e., our ability to infer (therefore guess, rather than know) other people's mental states in the attempt to predict and explain their behavior (Premack & Woodruff, 1978). The use of traditional paradigms such as false-belief tasks to assess ToM performance at different ages has often led to the argument that ToM reaches ceiling during childhood (Surian et al., 2007; Wellman et al., 2001), however recent findings on adolescence social development point towards a different direction. Also intuitively, considering the numerous aforementioned arguments in favor of a protracted cognitive and brain development during adolescence, it would be reasonable to hypothesize that something similar happens for abilities regarding social cognition, since many of those brain areas and functions are related to ToM (Aboulafia-Brakha et al., 2011; Pellicano, 2007). This network of brain regions involved in ToM, or mentalizing is referred to as the "social brain" (Blakemore, 2008). Indeed, by employing a task requiring on-line use of mentalizing abilities, Dumontheil et al. (2010), and Symeonidou et al. (2016), among others, have found that ToM continues to develop in late adolescence, without reaching a ceiling in late childhood. This “Director Task” (Keysar et al., 2000) required participants to actively take the perspective of a fictional director to follow specific instructions, and indeed the authors found a significant improvement of task accuracy between adolescence and adulthood, even when accounting for executive functions. In addition, Klindt and colleagues’ (2017) vast web pool of social cognitive skills (measured by a variety of tasks) has shown that “over the lifespan, people may rely upon distinct cognitive architectures when reading others' minds”, suggesting that as people age, they might rely on more controlled cognitive processes in mentalizing. This might tell us that during adolescence ToM might not simply be increasing, but it could also progressively rely more on effortful and controlled neurocognitive components, and less on automatic processes, which are prevalent in childhood.

Another significant aspect of social development, that is also related to ToM, is how we behave prosocially towards another person (Caputi et al., 2012), but perhaps more importantly how we adjust prosocial tendencies based on who that person is. Indeed, as briefly mentioned above, adolescents are increasingly able to distinguish between social contexts, especially in prosocial behavior. For example, during adolescence, people increasingly donate more to friends compared to strangers (Güroğlu et al., 2014; Padilla-Walker et al., 2015; van de Groep et al., 2022), something which Güroğlu and colleagues (2014) found to be mediated by (self-reported) perspective taking skills. Similarly, Tamnes et al., (2018) found an association between perspective taking as measured by the director task and self-reported prosocial behavior, together with an additional association between perspective taking and cortical thinning in regions related to social cognition and executive functioning, further suggesting the link between brain development and mentalizing abilities. This frequent association between perspective taking and prosocial behavior has often been intuitively accompanied by a further motivation to help someone (Warneken & Tomasello, 2006), also referred to as empathic concern. Indeed, it would be reasonable to assume that helping someone else would first require understanding that person's desires, intentions and perspective, as well as being emotionally involved and motivated to lend a hand. In this regard, empathy has been found to increase during adolescence (Allemand et al., 2015) and to predict individual differences in self-reported social competencies (e.g., communication skills) later in adulthood, highlighting a connection between empathy and other social skills.

Perspective taking skills are not only related to how generous we are with friends or strangers, but also with other abilities such as conflict resolution (Gutenbrunner & Wagner, 2016). Indeed, this ability continues its developmental trajectory in adolescence, given that adolescents increasingly employ negotiation as a peer conflict resolution strategies (compromise and third-party mediation), rather than being coercive or disengaging, i.e., withdrawing from conflict (Laursen et al., 2001), hinting at better cooperative attitudes towards peers. Furthermore, conflict resolution skills are related to the broader concept of social competence (Akgun & Araz, 2014), generally defined as how an individual affiliates with other people and forms close relationships (Burt et al., 2008). Social competence has been found to have an impact on psychological well-being, especially during adolescence, given that Gómez-López et al. (2022) have found a longitudinal association between increases in social competence and psychological well-being from early to late adolescence, which also extends to young adulthood (Romppanen et al., 2021).

Ultimately, from these findings we can gather that many social skills, including mentalizing skills continue to develop during adolescence (Dumontheil, Apperly, et al., 2010; Symeonidou et al., 2016), in parallel with changes in the social brain (Tamnes et al., 2018). These improvements are sometimes related to increasingly differentiated prosociality towards different interaction partners (Fett et al., 2014). Just as importantly, adolescents' conflict management skills become more similar to those of adults (Laursen et al., 2001), paralleled by an increase of complexity in social competence (Englund et al., 2000) and its association to psychological well-being.

1.2.4 Adolescence as a Sensitive Period

Up to this point adolescence has been broadly framed as a period of change, during which we can observe protracted development of neurophysiological characteristics (Bethlehem et al., 2022), as well as socio-cognitive abilities (Kilford et al., 2016). It could seem that adolescents are similar to children and adults in many domains (e.g., cognitive), only more developed compared to the former, and less to the latter. However, further research has additionally framed adolescence as a unique life stage, suggesting that it could represent a sensitive or even critical period of development (Fuhrmann et al., 2015). Indeed, some evidence does support this assumption.

Starting with changes in the brain, animal studies have shown that some aspects of brain plasticity could be unique in adolescence. Long-distance dopamine axon growth (Hoops & Flores, 2017), as well as an increase in dopamine innervation and concentration, have been specifically linked with adolescence (Larsen & Luna, 2018), and have been suggested to potentially underlie certain types of behavior that also peak during adolescence, relative to both children and adults. For example, Steinberg and colleagues (2018) have highlighted a cross-cultural peak of sensation-seeking towards the end of human adolescence, contrasted by the still developing self-regulation, which plateaus later during young adulthood.

Furthermore, Larsen and Luna (2018) have found correspondence in mice between mechanisms driving early sensory development during critical periods in childhood and those behind neurobiological and cognitive development in adolescence, thus suggesting a re-opening of critical period plasticity. This is in line with what transpires from Petanjek and colleagues' study (2011), who found that synaptic pruning continues during adolescence, and especially in the prefrontal cortex (Huttenlocher & Dabholkar, 1997), which is related to cognitive development.

During a time where cognitive abilities are still developing, adolescents seem to be showing heightened reward sensitivity in the ventral striatum, a region involved into reward processing, (Galván, 2013; Schreuders et al., 2018) something which dual systems (Steinberg et al., 2018) or maturational imbalance models (Casey et al., 2008) have considered to be a possible explanation for a variety of maladaptive behavior. Indeed adolescents are often associated with activities such as substance abuse, vandalism and general disregard of their own and others' safety, which are frequently grouped under broader category of sensation-seeking risky behavior (Defoe et al., 2022; Telzer et al., 2022; Zhang, 2022).

Interestingly, a common denominator of risky behavior across adolescence, which is more infrequent in other ages, is the presence of peers. Indeed, compared to adults, adolescents are more likely to risk in the presence of peers in simulated driving tasks, as well as focus more on the benefits rather than costs of risky behavior compared to being alone (Gardner & Steinberg, 2005). With the same task, Centifanti and colleagues (2016) found that adolescents were more likely to take a risk both when in presence of passengers who liked risk and encouraged to take a chance, and when passengers with risk preferences did not interact with them (passive influence), although to a lesser degree. Furthermore, Chein and colleagues (2011) found that the presence of peers while risking was also associated with a heightened reward system activation (ventral striatum) and decreased cognitive control (lateral prefrontal cortex) compared to being alone: this increased social reward sensitivity in turn predicted lesser resistance to peer influence.

Although these results are compelling, they do not address how preferences and choices of other peers, instead of merely their presence, could influence decisions during adolescence. Indeed social influence increases during adolescence (Sumter et al., 2009), highlighting how adolescents place great importance to how they are perceived by their peers. Accordingly, they are affected by social isolation to a greater extent compared to adults, both emotionally, meaning greater disappointment (Sebastian et al., 2010), and cognitively to a certain degree, in terms of reduced verbal working memory performance (Fuhrmann et al., 2019). In terms of preferences, young adolescents are more likely to change their perception of risk in the direction of other adolescents' responses, while younger and older participants are more influenceable by adults (Knoll et al., 2015), showing that adolescents value their peers' views over those of grown-ups. Traditionally, findings regarding peer influence during adolescence have been interpreted as maladaptive and linked to more impulsive behavior, thus favoring models of maturational imbalance (Casey et al., 2008). This framing of adolescence seems in line with a conceptualization of adolescence as an age of "storm and stress" (Buchanan & Bruton, 2016; Buchanan & Hughes, 2009). For example, heightened social influence during adolescence could lead to maladaptive forms of sensation-seeking, thus to unsafe behavior (Goldstick Jason E. et al., 2022). In this sense, social influence might represent an issue that is especially prominent during adolescence.

In contrast, recent studies are showing that heightened social influence during adolescence might be a developmental feature of adolescence, not a "bug", meaning that many previous findings might have focused on the downsides of some generally adaptive (and perhaps fundamental) developmental process. Indeed, Reiter and colleagues (Reiter et al., 2019, 2021) have highlighted how adolescents might be more susceptible to other peers' decisions for the purpose of reducing their own uncertainty, thus learning more about themselves by learning about others. For example, they found that the choices adolescents made after observing the choices of their peers were associated with longer response times (2019), suggesting that peer influence may not always be impulsive, but effortful. In the same study, adolescents who were more influenced by their peers were shown to also be better at predicting the preferences of their peers, something that could be very helpful to navigate peer environments. In line with this, the two studies by Reiter and colleagues found that susceptibility to social influence during adolescence is related to social integration, also longitudinally. Similarly, using agent-based modelling, Ciranka & van den Bos (2021) have illustrated how those frequent patterns of peak risk-taking during adolescence might stem not from a motivational drive of sensation seeking, but from a need to learn from others following changes in the environment, which might also help them reduce losses in the future. They also discussed the importance of exploratory behavior during this age, in relation to learning from others, and how this tendency to explore novel environments (thus take risks) may also give rise to the typical inverted-U shapes found in adolescence (e.g., sensation-seeking).

Finally, heightened social influence during adolescence might also raise opportunities for prosocial behavior. For example, adolescents have been shown to be more likely than adults to engage in charitable donations if they see other peers doing the same (Chierchia, Piera Pi-Sunyer, et al., 2020). In the same prosocial influence task, adolescents also took longer to decide when prosocially influenced, but not when conforming to a selfish peer.

Overall, these studies are more aligned with a different theory of adolescent development, the Life-span Wisdom Model (Romer et al., 2017), which argues in favor of the existence of risk-taking behavior more directed towards learning and exploration, instead of only impulsivity, which peaks during adolescence not because of a motivational craving for risk, but rather a need to venture into new contexts which, given the unfamiliarity, require bolder behavior. This increase in risky behavior, moreover, is paralleled by continuous development of cognitive abilities (also considering increased response times previously mentioned), which interact with exploratory tendencies and thus contribute to generating wisdom throughout life. Ultimately, our adult self might benefit from the risky decisions of adolescent self.

Heightened social influence during adolescence corroborates the idea that adolescence might be a sensitive period for social development, during which social experiences might play a particularly important role in social development. Intriguingly, animal studies have also corroborated this notion. For example, one study showed heightened alcohol consumption by juvenile mice in the presence of peers, compared to adult mice (Logue et al., 2014).Further, studies have shown that social deprivation can lead to heightened negative consequences on brain and behavioral development if it occurs during adolescence, compared to other ages (Orben et al., 2020). In addition, more than half of all psychological disorders, such as schizophrenia, anxiety, eating and mood disorders are first diagnosed during adolescence (Paus et al., 2008; Solmi et al., 2022).

Taken together, these studies suggest that childhood might not represent the end of the line for critical development, but rather a “window of opportunity” which re-opens during adolescence (Fuhrmann et al., 2015; Larsen & Luna, 2018).

1.3 Strategic Development

Adolescence is also an age where people make consequential choices for the first time in their lives outside of a family circle and into a peer-focused environment, while obtaining increasing autonomy and the accompanying responsibility (Boyden et al., 2019; Zimmer-Gembeck & Collins, 2006). Consequently, decision-making abilities in relation to changes of context start gaining even more relevance than before. Furthermore, as an age of social re-orientation, peer interactions become progressively more important than interactions with caregivers during adolescence, with peers being perhaps less forgiving than parents. In line with this, adolescents have been suggested to start grasping how the outcomes of certain decisions depend not only on their intentions, but on those of their peers as well (Crone & Fuligni, 2020). With this, adolescents also start experiencing how sometimes individual goals can overlap with collective ones, and in other cases be at odds, thus realizing how obtaining what they want within a social environment is more complex compared to being on their own.

These changes are fundamental in the development of strategic social behavior (Güroğlu et al., 2009; Steinbeis et al., 2012), which can bridge the gap between self- and other-interest and in general facilitate navigation through new social contexts. Accordingly, social re-orientation might also involve an increasing need to be strategic in social interactions with peers, whereas the same ability might not be as prevalent in interactions with caregivers. In other words, since adolescents spend more time with their peers and give increasing weight to what they do or say, they might increasingly keep in mind the preferences of others, particularly their peers, when interacting with them, thus becoming more strategic.

In investigating the development of strategic social behavior, game theory can be an invaluable resource, since it provides "general mathematical techniques for situations in which two or more individuals make decisions that will influence one another's welfare", both in terms of conflict and cooperation (Myerson, 1991). Game theory has classically approached decision-making of agents by giving little or no space to social or emotional factors and individual differences, in favor of logical thought-processes, thus without tapping into "the richness of the psychological world" (Krueger et al., 2020). Critically, predictions based on this purely mathematical approach have been disproven many times by empirical observation of people's decision making in laboratory experiments (C. F. Camerer, 2003; Henrich et al., 2005).

At the cost of lower controllability, the more recent discipline of behavioral game theory seeks to integrate psycho-social factors, with the advantages and disadvantages that they bring, to purely cognitive ones in investigating social decision-making (Bonau, 2017; Gintis, 2011). This approach allows the generation of mathematical models which could ideally predict people's decisions in specific situations, all the while being open to falsification and thus updating based on actual behavior and its psychological underpinnings (Fehr & Schmidt, 1999; Sanfey, 2007). Indeed, behavioral game theory applied to developmental psychology is able to offer new methodologies aimed at investigating social development through more controlled decision making tasks in situations of social decisions (Gummerum et al., 2008). These tasks aim to capture the core strategic aspects of frequent social dilemmas in psychological and, more generally, biological research (Archetti & Scheuring, 2012; Beckenkamp, 2006), such as the prisoner's dilemma (Rapoport & Chammah, 1965). One of the ideas behind this approach is that evolutionary demands might have shaped brain and behavoiur to solve such social dilemmas, in order to profit from them, and generally gain from social interactions (Dawes, 1992). In other words, our ability to engage with these dilemmas is not simply a by-product of our cognitive and social evolution, but rather the emergence of such problems might have partly promoted our socio-cognitive development in order to approach them more effectively.

To investigate the potential developments of strategic social behavior during adolescence, various components of strategic interactions have been investigated through a behavioral game theoretic approach. Fett and colleagues (2014), using the trust game paradigm, found that adolescents with higher perspective taking abilities showed higher levels of default trust towards others by entrusting their resources, but also that they displayed increased sensitivity to perceived unfairness when the trust was broken, thus exhibiting more strategic behavior when learning who to trust or not trust based on repeated interactions.. Sijtsma et al. (2023) found similar results with a longitudinal design, with an increasing initial trust with age, but also increasingly adaptive trusting, i.e., investing mostly on trustworthy counterparts, which (in girls) was in turn related to perspective taking abilities. Similarly, adolescents were shown to be increasingly sensitive to the intentions of their counterparts, not just their actual choices, reciprocating prosocial actions more when these were intentional (van den Bos et al., 2011). These higher levels of trust were in turn associated with greater activity in brain areas involved in mentalizing and executive functions, which increased with age, once again showing a behavioral and neurobiological shift towards other-oriented thinking in adolescence.

Using a variant of the “ultimatum game”, in which participants had access to the proposer’s choice alternatives, thus better allowing to infer their intentions, Sul et al. (2017) further managed to differentiate between inequity aversion (classically displayed in the ultimatum game by refusing unfair offers) and reciprocity. They found that with increasing age people were more willing to accept disadvantageous offers when the proposer had no better option, compared to having the possibility to offer more, even if the offer was the same. This effect of age on reciprocity was further mediated by cortical thinning in mentalizing areas, again suggesting a growing association between increasing strategic behavior (accepting any amount when no alternative is possible) and brain development associated with social cognition.

Furthermore, we can detect an increase of strategic use of social cues not only in reciprocating trust and generally understanding intentions, but also prosocial behavior, since we already discussed that adolescents tend to donate more to friends compared to strangers (Güroğlu et al., 2014; Padilla-Walker et al., 2015). Arguably this result can be interpreted as strategic because ultimately friends are more likely to reciprocate generous behavior, which enables a virtuous cycle benefitting not only the receiver, but also the donor. Indeed, adolescents are not only becoming increasingly specific in their generosity, but also growing to be more mindful of their own resources, by choosing to give lesser amounts when forced to be parted with big sums, but greater amounts when choosing among smaller quantities (van de Groep et al., 2022), thus suggesting greater cost-benefit consideration in their choices on top of higher context-dependency of giving. In addition to higher reciprocity towards trustworthy individuals, adolescents are also increasingly sensitive to violations of social norms such as fairness, as shown by increasingly proportionate third party punishment of offenders, based on the severity of their violation (Gummerum et al., 2020; House et al., 2020). This suggests that adolescents not only try to be initially trusting (Sijtsma et al., 2023), but they also expect others to do the same, which highlights the importance of punishment of norm violations to foster collective cooperation (House et al., 2020). In addition to this, the magnitude of the punishment does not simply increase with age, but it rather hints towards a more sophisticated sensitivity towards other people's choice to be selfish.

Many of the examples above generally refer to an increase of strategic behavior occurring from a more strategic use of cues from the social context, such as someone else's willingness to be trusting (e.g., Sijtsma et al., 2023; van den Bos et al., 2011), or simply knowing that the receiver is a friend (Güroğlu et al., 2014; Padilla-Walker et al., 2015; van de Groep et al., 2022). Nevertheless, it is unknown whether and how, during adolescence, there could also be an increase in implementation of cues from strategic contexts, that is, the type of game involved in terms of incentives, options and demands, independent of social context. In game theory, strategic contexts have been also divided into two main categories, named strategic complements and substitutes, which are known to foster cooperation and competition respectively.

Indeed, according to Camerer and Fehr (2006), strategic incentives play a crucial role in affecting the outcomes of social interactions, which take place between self-regarding individuals (close to the canonical model of a rational economic man), and people with other-regarding preferences (who value other people's outcomes, both positively and negatively). Specifically, cooperation is triggered when decisions of few other-regarding individuals incentivize the remaining majority of self-regarding others to cooperate, i.e., their choices show the benefits of caring about other people's decisions and their outcomes. Similarly, competition is instead triggered when the decisions of a few self-regarding individuals steer the other-regarding individuals to behave like them and solely focus on their own outcomes. In other words, the classical model of a rational and self-focused economic man fares better in a competitive context which rewards minding own self-interest, while an other-regarding individual does better in strategic contexts where the agents are rewarded for taking into account the others' decisions.

A related concept to strategic complements vs. substitutes distinctions, highlighting the role of the strategic context, is game harmony. This describes "how harmonious (non-conflictual) or disharmonious (conflictual) the interest of players are, as embodied in the payoffs" (Zizzo & Tan, 2002), which could represent another way of describing complementarity (harmony) and substitutability (disharmony). It follows that, in harmonious or strategic complement games, henceforth "cooperation", the interests of the agents match (i.e., opting for the same choice is beneficial to everyone. In contrast, in games with strategic substitutes or disharmonious games, henceforth labelled "competition", all participants cannot simultaneously maximize their payoffs, thus similar strategies can offset one another and be detrimental.

The question of this dissertation is how the ability to distinguish between strategic contexts changes with age during adolescence, specifically in terms of cooperation (or complementarity) and competition (or substitutability), which we can consider as two opposite declinations coordination (Chierchia et al., 2018). The evidence sketched suggests that adolescence is a period of protracted neural plasticity and social development, perhaps a sensitive or critical one, during which peoples' decision making makes increasingly strategic use of social cues to guide social decision making. This raises the hypothesis that adolescence might also represent an appropriate candidate for investigating the emergence of higher forms of social behavior such as strategic abilities. Finally, coordination games constitute a potentially powerful tool which might be sensitive to the development of this ability to strategically interact with others.

1.4 Coordination Games

As previously hinted, coordination games are part of a broader class of games belonging to game theory, meaning that they involve analyzing options and incentives available in multi-agent decision problems, in which the outcomes of ones choices can depend on the choices of others (Myerson, 1991). Coordination games can involve choosing between a certain payoff (albeit often smaller) and a riskier (often higher) “social” option which involves cooperating or competing with others.

Since this study delves into strategic decisions throughout adolescence, it is worth mentioning the distinction between risk as seen in game theory/economics and developmental psychology. The former discipline defines it as a quantifiable uncertainty when making decisions, i.e., wherein the agent is aware of the probability for different outcomes, but not of the specific consequences of one’s actions (e.g., knowing the 50% probability of getting Tails in a coin flip, but being unsure whether it will truly happen) (Platt and Huettel 2008; Loewenstein, Rick, and Cohen 2008; Mohr, Biele, and Heekeren 2010 etc.). Developmental psychology, on the other hand, has a rather behavioural and broader view of risk-taking, frequently defined as engaging in activities possibly associated with adverse, maladaptive outcomes (Boyer, 2006; Willoughby et al., 2021). This work mostly considers the economic aspect of risk-taking, with the difference of the unknown probability of receiving a reward when risking in certain circumstances in this case, which some could define as uncertainty (Knight, 1921).

Returning to coordination games, these decisions (risky or safe) can be investigated by looking into the optimal outcome for the players involved, which game theory tries to do by finding Nash equilibria i.e., a set of strategies that lead to a state in which no agent has an incentive to unilaterally deviate from his/her choice (Chierchia &

Coricelli, 2015), so the optimal decision-making route. The problem of coordination games, however, is that they involve multiple Nash equilibria. This gives rise to a problem of equilibria selection (Cooper et al., 1990), labelled often as strategic uncertainty (Van Huyck et al., 1991). Because of this, coordination games have been said to constitute "The hardest problem of game theory"(C. F. Camerer, 2003). In simple words, among all the games in game theory, coordination games are particularly problematic because they cannot be solved by deductive reasoning alone, they have no right or wrong answer. This might also make coordination games particularly suitable environments to study strategic abilities that are not uniquely based on deductive reasoning, but also on social abilities.

In regards to this open matter, Chierchia and colleagues (2018) have investigated whether this strategic uncertainty is similar between cooperating in "games against others" and playing "games against nature" (Figure 1). Specifically, the available decisions in this experiment consisted of uncertain (or risky) and safe choices (of varying values) in both cases, with "games against others" representing coordination, divided into cooperation (coordination or stag-hunt) and competition (anti-coordination or entry game). The authors intended "games against nature" as two lotteries, one risky (probability to obtain the risky option of 0.5) and one ambiguous (unknown probability).

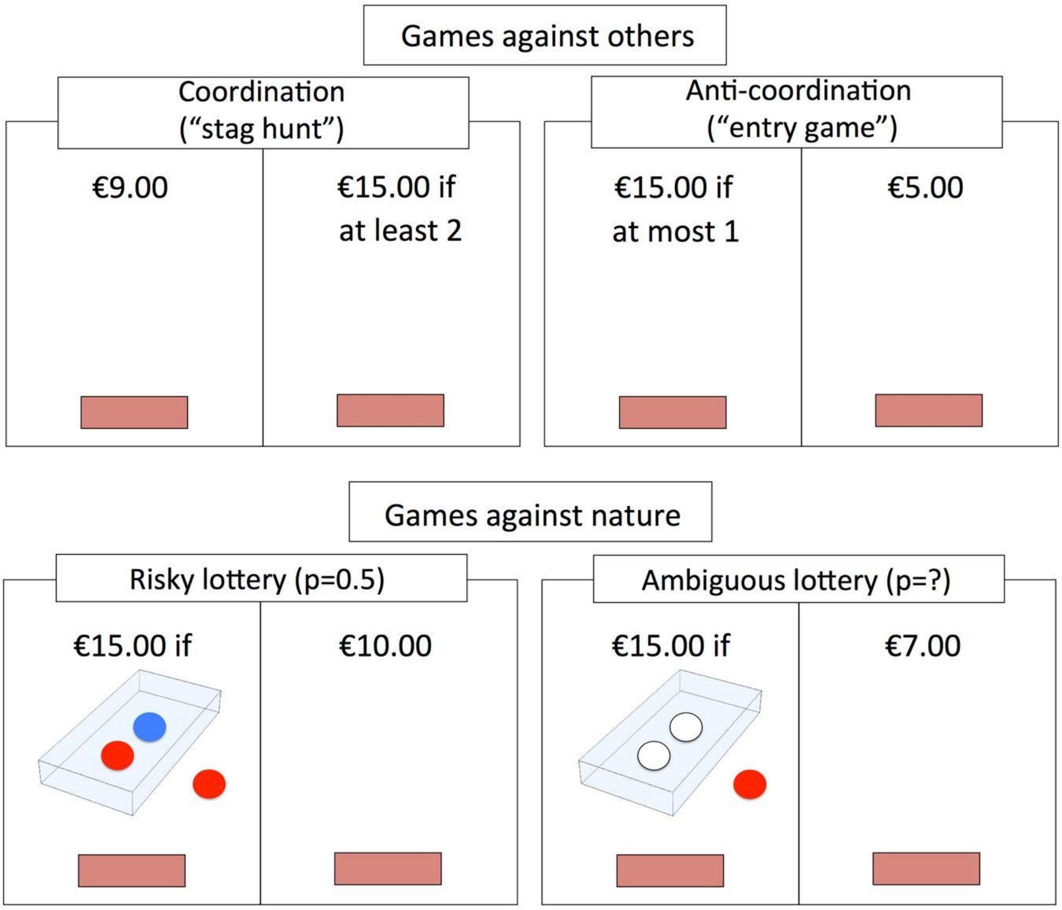

Figure 1. Illustration of the coordination game, reprinted with permission from Chierchia et al. (2018). The figure shows the possible choices among different conditions, involving a risky high-paying option and a safer lower-paying option. The outcome of choosing the risky option depended on the condition, involving cooperation (or "stag hunt"), competition (or "entry game") and the two lotteries.

They found that adults seem to change their decisions within the two strategic social contexts by exhibiting more propensity towards risking in cooperation compared to competition and lotteries (Figure 2). In other words, when risking alongside a player yields the maximum reward, adults are more willing to take a chance compared to when collective risking results in no prize for the people involved: nonetheless, coordination failures were surprisingly not infrequent. Additionally, players made decisions differently between strategic social contexts and games against nature: this difference was more noticeable between cooperation and lotteries, while competition seems to be akin to the ambiguous lottery, showing apparent similarity between competing against people and playing against nature where the outcome is unpredictable.

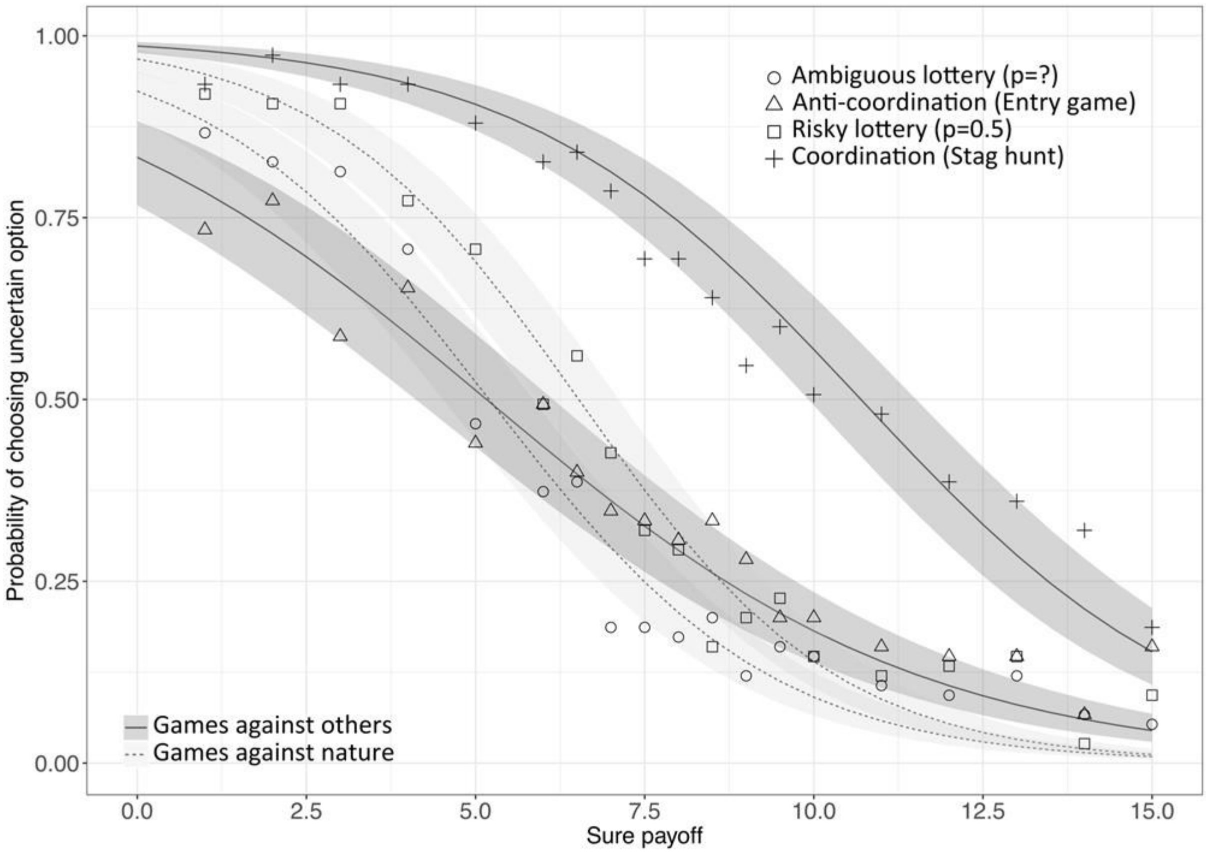

Figure 2. Visualization of trial-level uncertain choices (y-axis) relative to each sure payoff value (x-axis), across social (darker shades) and non-social (lighter shades) environments, with symbols shapes representing each condition, and positions indicating percentages of UP choices in each environment for each SP value. Reprinted with permission from Chierchia et al. (2018)

This last remark is true when considering choices whether to risk or not (specifically, certainty equivalents), however competition was associated with significantly greater switching between the two alternatives (which highly correlates with entropy, or noise), in parallel with longer decision times. Simply put, adults switch between risking and playing safely, but also dwell more on these choices in competition more than they do in a lottery (and cooperation), thus displaying an aversion to competition.

Why does competition elicit these different behavioral signatures, relative to cooperation? To understand the "why" of this considerably different pattern in competition compared to cooperation, we can look into cognitive hierarchy theories (Chong et al., 2005). Indeed, models of hierarchical or strategic reasoning (i.e., reasoning about other people thinking about us thinking about them etc.) predict increased switching as the level of reasoning increased, but only in competition. This highlights a potential special relation between non-verbal reasoning about other people's choices and repeatedly changing own decisions in competition, which has usually been framed as noise instead. Specifically, switching is hypothesized to be an indicator of inconsistent (or noisy) decisions in cooperation (or stag-hunt), while it is potentially compatible with higher recursive reasoning in competition (or entry game; Nagel et al., 2018).

In other words, going back and forth from safe to risky choices in cooperation, as the value of the sure payoff increases, might indicate lesser understanding of game dynamics and poorer strategic abilities in cooperation, while the same switching in competition might denote greater inferential effort about the anonymous counterpart's thoughts and choices. In turn, longer response times might be due to greater inferential effort, rather than indecisiveness.

Overall, the results from this study indicate that risk-taking differentiates mostly cooperation from the other environments (Figure 3), while RTs and switching differentiate competition from other environments (Figure 4), with the latter being possibly tied to recursive/hierarchical reasoning in this condition. That is why all three measures (risk, switch and RTs) are fundamental in understanding how and whether a person differentiates between different strategic environments. More specifically, these measures can be used as indicators of strategic ability, i.e., the ability to adapt choices to different strategic contexts, such as of cooperation and competition.

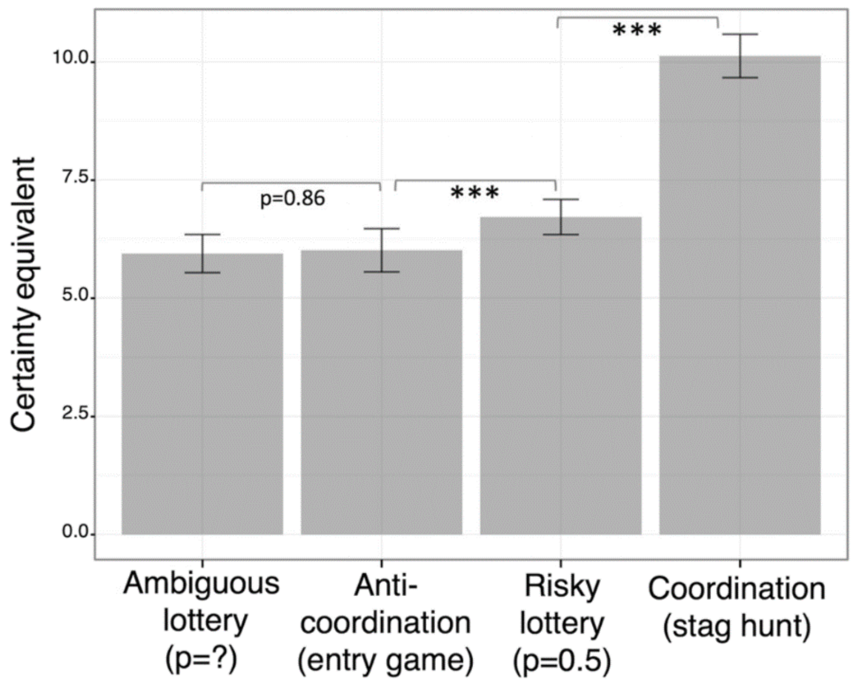

Figure 3. Mean of certainty equivalents across different conditions. Greater certainty equivalents differentiated cooperation (or “stag hunt”) from both competition (or entry game) and the lotteries. Reprinted from Chierchia et al. (2018). ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$

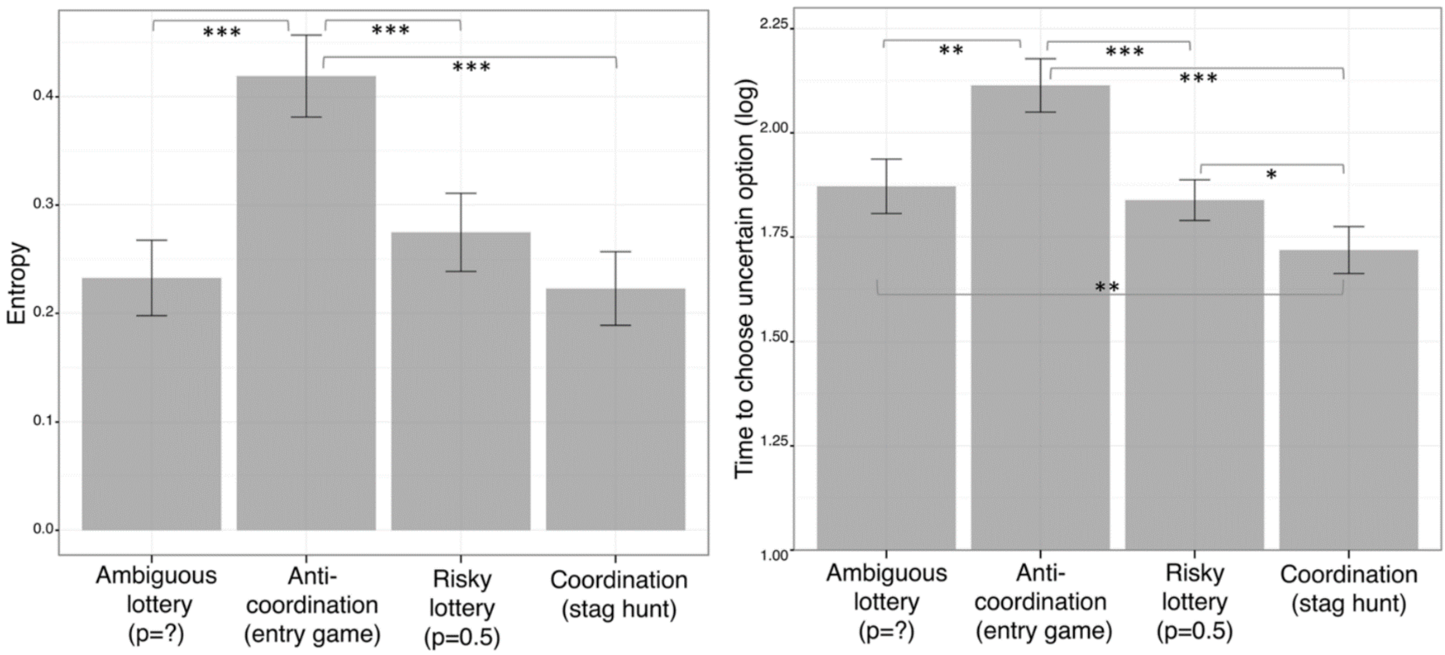

Figure 4. Left: visualization of average switching amount (entropy) across different conditions (x-axis). Greater switching differentiated competition from cooperation and the lotteries. Right: response times (y-axis) across different conditions. Longer response times were related to a competitive context while shorter ones to a cooperative environment. Greater switching and RTs were indicators of competitive environments. Reprinted with permission from Chierchia et al. (2018)

As we extensively argued in the previous sections, non-verbal reasoning abilities improve markedly during adolescence (e.g., Chierchia et al., 2019; Krogsrud et al., 2021; Tamnes et al., 2010), which could predict changes in coordination patterns with age, especially in competition. Coordination games, however, are not only sensitive to strategic cognitive processes, but also to social contextual factors, since Chierchia and colleagues (2020; 2015) showed in two occasions that who we play against and how we perceive them might affect our choices. Indeed, people are more propense to risk in cooperation if they are playing with a friend or someone reportedly more similar to them, but also more risk averse in competition in the same situations.

Nonetheless, despite this well-defined picture concerning adults by Chierchia et al. (2018), little is known about social decision-making and strategic reasoning in coordination games concerning children and adolescents, and specifically whether and how they choose to cooperate prosocially with others, or compete for the best individual outcome, and in what way these choices compare to playing against nature.

Some of these matters have already been investigated with an economic approach through different games, with results broadly suggesting an increase in strategic abilities and rational choices (Sutter et al., 2019), yet there is still no clear picture regarding ability to differentiate between strategic contexts in age groups younger than adults, especially for games involving playing with others. Regarding the last point, Westhoff and colleagues (2020) have investigated the development of the ability to adjust to cooperative and cooperative environments. They found that even from late childhood people managed to adapt well to uncooperative (or competitive) environments, however they started to adjust to cooperative ones only during adolescence. Crucially, by environments they intended social ones, as in the type of person they were interacting with (e.g., friendly or unfriendly), and not the type of game involved (e.g., cooperation or competition game). Although these results do not offer insight regarding strategic contexts related to types of coordination games, they represent a potential starting point in considering age-related differences in the ability to differentiate between diverse strategic contexts and how adolescents may adapt to them.

Ultimately, decisions amongst others are the outcome of social, cognitive and motivational processes, all of which undergo protracted development and changes during adolescence (e.g., Blakemore & Choudhury, 2006; Gardner & Steinberg, 2005; E. E. Nelson et al., 2005), which leads to the hypothesis that more sophisticated forms of social and strategic behavior might emerge during this life stage. Indeed, since decision-making processes interact with both social and strategic contextual factors (Bruch & Feinberg, 2017; Chierchia, Tufano, et al., 2020; Lee & Harris, 2013), investigating them during adolescence might shed more light on how we learn to make decisions while keeping others in mind, which might also tell us more about how we might collectively solve pressing matters such as social dilemmas (Dawes, 1992).

A reasonably suitable method to do so can be found in game theory, and more specifically in coordination games. As multiple studies have shown (Chierchia et al., 2018; Chierchia, Tufano, et al., 2020; Chierchia & Coricelli, 2015; Westhoff et al., 2020), coordination games are a simple yet highly informative task which provides us with a way to explore how people might adjust their decisions with age based on the strategic context they are in while also having to think about other people's possible choices.

Specifically, and based on the research by Chierchia and colleagues (2018), the aim of this work is investigate the possible emergence of strategic coordination abilities so by focusing on how much adolescents might risk for a maximum reward or opt for a safer prize (of varying amounts) differently between strategic contexts, but also how often they switch between those two alternatives.

Additionally, we ask ourselves how much they dwell on their choices so that we can understand better, also thanks to switching amounts, whether choice patterns might be better explained by a lack of understanding (noise, or entropy), or rather greater hierarchical reasoning levels. Finally, through coordination games, we also assess how much people's choices under varying contexts might turn out to be more or less advantageous to them, by looking at their total payoff.

By bearing in mind not only the previous studies (e.g., Chierchia et al., 2018), but also the outcomes of both extraordinary and small-scale feats of human cooperation mentioned at the very beginning, we know not only that coordinating with others is clearly present, but also essential in adulthood. Furthermore, since interacting with other peers is increasingly prioritized during adolescence (E. E. Nelson et al., 2005), and given how this age is unique in many ways from a developmental perspective, extending coordination games to this life stage could tell us at which age we might observe the emergence of the ability to strategically coordinate with others.

2. Methods

2.1. Participants

596 Italian-speaking participants (215 males, 375 females) participated in the study, among school children (*N* =150, *M* age =10.5, *SD* =0.63, with an age range between 9 and 11), adolescents (*N*= 147, *M* age = 12.8, *SD*=0.75 age range between 12 and 15) and young adults (*N* = 299, *M* age = 21.4 *SD* =3.33) (Table 1). All participants were native Italian speakers, had normal or corrected to normal vision and were naïve to the purpose of the study. Informed consent was obtained from all participants before the experiment. The protocol was approved by the psychological ethical committee of University of Pavia (ethics approval number 113/22) and participants were treated in accordance with the Declaration of Helsinki. Children and adolescents were recruited through a–request submitted to the principal's office of their respective schools, whereas adults were psychology students recruited through University newsletters.

	Children	**Adolescents**	**Adults**
N	150 (87M, 63F)	147 (76M, 71F)	299 (52M, 241F, 6 N/S)
Age Range	9-11	12-15	18-48
Age Mean (SD)	10.5 (0.63)	12.8 (0.75)	21.4 (3.33)

Table 1. Participants' demographics table. 6 adults preferred not to specify their gender (N/S).

2.2. Materials

2.2.1. Coordination Games: Cooperation Vs. Competition

Participants were told that they would play two types of games with an age-matched peer, who would receive the same instructions and see the same options as they did. Both games are drawn from the behavioral game theory literature. One game was a stag hunt (also called assurance game) (Heinemann et al., 2009) and the other an entry game (C. Camerer & Lovallo, 1999). For simplicity, we henceforth refer to these games as cooperation and competition, since they foster this type of behavior (C. F. Camerer, 2003). In both games participants were presented with a choice between two options represented by two bags containing virtual gold coins (Figure 5): one bag represented a sure payoff (SP). If chosen, this corresponding amount of gold coins was always awarded, regardless of what one counterpart chose. This SP value varied pseudo-randomly from 1 to 15 from trial to trial, though no feedback was provided between trials. The second option was an uncertain payoff (UP) which could potentially lead to either the maximum payoff of 15 gold coins or nothing. Receiving 15 or 0 coins in the UP depended on the game. During the instructions, the SP and UP options were labeled as “mini treasure” and “super treasure” respectively. Participants were told that the goal of these games was to obtain as much gold as possible.

In the cooperation game the participant was awarded with the maximum payoff (15) after choosing the UP if and only if his/her anonymous counterpart chose this same option as well. In other words, both participants maximized their points by choosing the uncertain option. In contrast, in competition, one earned the maximum only if they chose the uncertain option and their counterpart did not. If both participants chose the uncertain option, both earned 0. Throughout the instructions and task, the words “cooperation” and “competition” were never used, since participants were to understand the cooperative and competitive nature of the games based on the incentives alone. Correspondingly, during the task, the cooperative condition was labelled as the “only if both” condition, while competition as “only if alone”, each with corresponding illustrations. Throughout the trials, the position (left-right) of the two options was randomized. The UP option could always be identified by the distinct game illustration and description (i.e., “only if you” or “only if both”) on top of one of the two bags (e.g., when presented with a SP of 15 and an UP of the same value, the participant could recognize the UP by the illustration above this choice, whose content changed based on the current condition).

Each participant completed both games, consisting of 15 trials for each condition, so 30 in total, for which he/she did not receive any real monetary compensation. Importantly, after each trial, no feedback was provided revealing the outcome of the choices. This was done to avoid effects related to learning and belief updating and focus on decisions in one-shot games involving different options.

The experiment was implemented with Gorilla Experiment Builder (www.gorilla.sc) (Anwyl-Irvine et al., 2020). Therefore, all tasks were carried out using electronic devices (mostly laptops, a few PCs and tablets).

2.2.2. Lottery

Both the conditions above were social, in that they involved coordinating choices with other people. The lottery condition was developed as a non-social control. This condition involved the same SP (guaranteed to be secured when chosen) and UP options as the coordination games, thus identical potential incentives. As in the coordination games, if the SP was chosen, that amount of gold coins was gained for sure. In contrast, if participants chose the uncertain option, they obtained the maximum payoff depending on an extraction from a random (non-social lottery). To make this ambiguity clear to the players, during the explanation of this condition we drew participants' attention to an empty opaque box in which we openly placed two blue balls and two red balls, closed it, and then rattled it. At this point, another experimenter removed two balls from the box without letting the participants or the other experimenter know which ones, and finally closed the lid again. Consequently, the box might have contained two blue balls or two red balls, or one blue and one red. It was then explained to the participants that, after the end of the session, a single ball would be randomly drawn by a computer, and that the lottery payoff would depend on its color. Specifically, the UP could be won only with a red ball extraction and, since the color of the two balls remaining in the box was unknown, the probability of obtaining a red ball was unknown as well. This is done with the purpose of matching the fact that, in games with other people, the probability that others will choose the SP or UP is unknown.

This condition was identified by the label "random draw" and, similarly to the coordination game, its illustration was positioned over the UP choice to indicate that this was the risky option between the two. As in coordination games, SPs and UPs are named "mini treasure" and "super treasure", respectively. The lottery game was played for 15 trials just like the coordination ones: the order in which these 3 games are completed was randomized (e.g., one participant could start with lottery, another with cooperation etc.), although they were all played in one session and in blocks, meaning that the three games were not mixed, so each time one started one of the three games, he/she played it for 15 trials. This was done to reduce possible confusion due to excessive task switching. The 3 games are displayed in Figure 5 along with the choices.

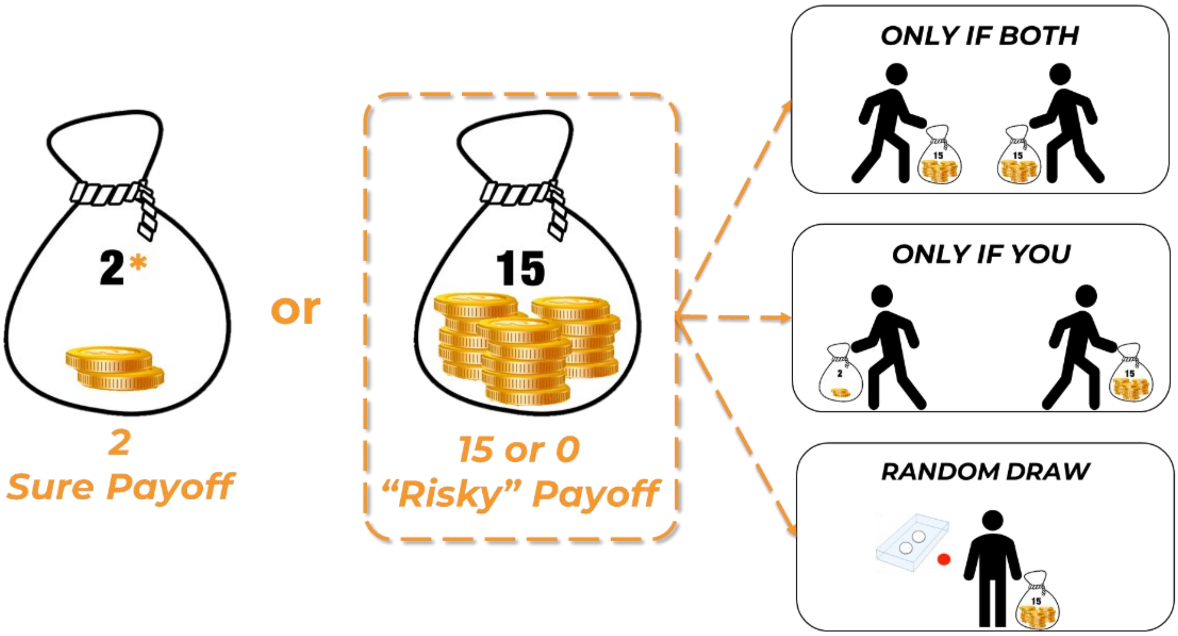

Figure 5. Summarized representation of coordination games (cooperation or "only if both" and competition or "only if you") and the random lottery (random draw). Participants could choose between a sure payoff and an unsure or "risky" payoff, whose choice outcome depended on the condition, similarly to Chierchia et al. (2018). The illustrations on the right are used to both identify the condition the participant was playing in and the UP choice between the two (placed above the bag). *The SP value pseudo-randomly varied between 1 and 15.

2.2.3. Game Comprehension

After the instructions, to ensure that the participants have understood the rules, they also completed a questionnaire before doing the task. Participants answered to true/false and multiple-choice questions across 4 areas which assessed knowledge regarding: 1) general rules, 2) coordination, 3) competition and 4) lottery trials. The general rules involved 5 true or false questions regarding instructions common to all three games. For example, participants were asked whether the lottery and coordination games involved any feedback, how to identify the UP between the two choices or how they could obtain the SP etc. There were 10 multiple choice questions regarding the coordination games (5 for cooperation, 5 for competition), mainly assessing correct answers to hypothetical choices (Figure 6) (e.g., in "only if both", if you pick the super-treasure and the other person chooses the mini-treasure, how much do you get?). As for the lottery game, the multiple-choice questions were 3, and similar to those of the coordination game. During this time, they were allowed and encouraged to ask further questions to the experimenters concerning how to play the game appropriately.

Since the aim of this questionnaire was to clear any doubt, they received feedback for each answer through a green tick in case of correct responses, and a red cross in case of erroneous ones. They could not progress through the questionnaire (and later access the games) unless they eventually selected all the correct answers.

Furthermore, we counted the number of incorrect responses, and later used this index as a "Comprehension" measure related to the instructions given. Specifically, we also took into account multiple erroneous attempts for each multiple-choice question. A participant giving multiple incorrect answers to the same question or making overall many mistakes was considered to have a lesser understanding compared to someone with no or fewer mistakes.

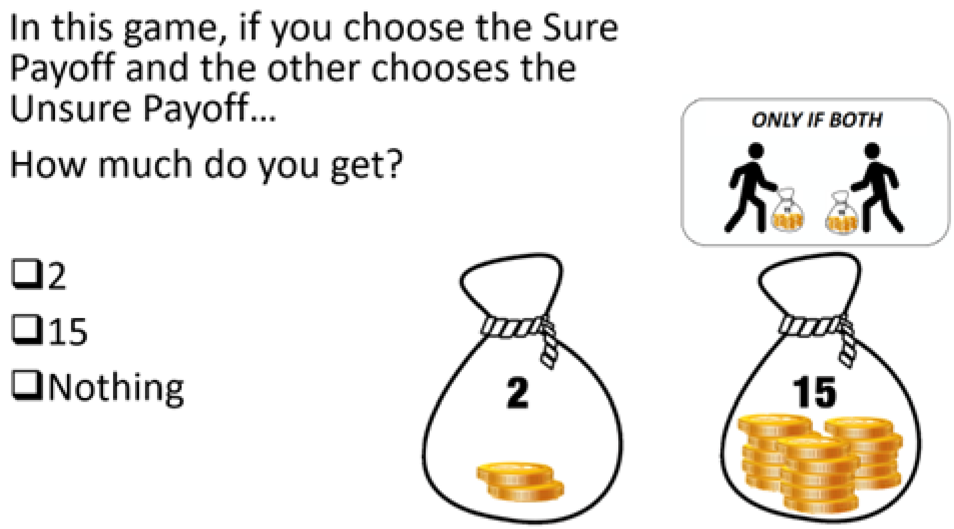

Figure 6. An example question from the pre-coordination questionnaire showing multiple answers to the hypothetical question, which refers to the cooperation condition. To understand which condition the question refers to (and answer correctly), the participant needs to recognize the corresponding illustration on the right.

2.2.4. Self-Referential Vs. Other-Oriented Strategies

After having played through a session of the three games, the participants were administered a questionnaire which assessed self-reported strategies and awareness during the task. It consisted of 8 questions concerning comparisons between games, such as: “Have your choices changed between cooperation and competition?”, which were assessed with yes/no/I don’t know responses. In the case of an affirmative answer, the participants were also allowed to motivate their strategy with an open question (If your choices have changed, how?). Finally, the participants were also asked how much they thought about themselves getting the reward or the anonymous counterpart obtaining it in the coordination games (e.g., in coordination, how much did you think about what you wanted to get?), which they could indicate with a slider going from 0 to ten (Figure 7).

There were no correct or incorrect answers in this questionnaire, given that the aim was to assess whether the participants actively changed their strategic approach and by extent how aware they were about differences between the three games.

The main measure of interest were the visual analogue scales (1-10) in terms of difference between how much the participants were thinking about others vs themselves during coordination and competition tasks.

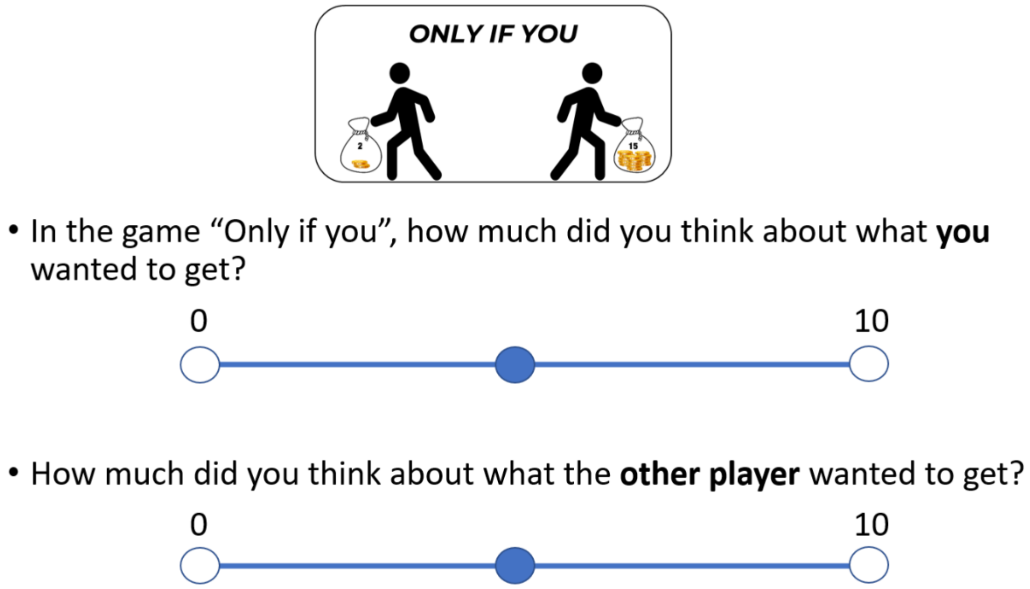

Figure 7. An example question from the post-coordination questionnaire involving competition (only if you), specifically asking to quantify the amount of thought given to self- vs. other- directed strategic thinking by placing the blue dot anywhere between 0 and 10 (included).

2.2.5. Reasoning Ability

The Matrix Reasoning Item Bank (MaRs-IB) (Chierchia et al., 2019), is an open-access non-verbal abstract reasoning task consisting of incomplete matrices containing abstract shapes (Figure 8). Similarly to Raven's Progressive Matrices (Raven & Raven, 2003), in the MaRs the participants were required to recognize the relationship between matrices at different levels of complexity and choose the correct missing square among 4 for 16 trials. During the task they were not given any feedback regarding the accuracy of their choices, and they were asked to complete every "puzzle" as quickly and accurately as possible. The participants had 30 seconds to complete each matrix and, in case of indecision, they were notified with a 5 second countdown which signaled that the task was about to proceed to the next picture.

This task has been recently validated in adults (Zorowitz et al., 2023), showing good reliability and convergent validity. It is a flexible tool that spans across a wide range of difficulty levels and possesses a good level of discrimination. Indeed, using this task, Chierchia and colleagues have replicated the many aforementioned findings (e.g., Hartung et al., 2020; Wendelken et al., 2017) of increasing non-verbal cognitive abilities during adolescence (Chierchia et al., 2019), showing how the MaRs is sensitive to age-related improvements in reasoning accuracy during adolescence.

Regarding the way we measured performance, although we also recorded reaction times, focus was given towards the means of correct answers across 16 trials, since all participants had a fixed time limit on each trial. Greater MaRs scores are interpreted as higher non-verbal reasoning abilities.

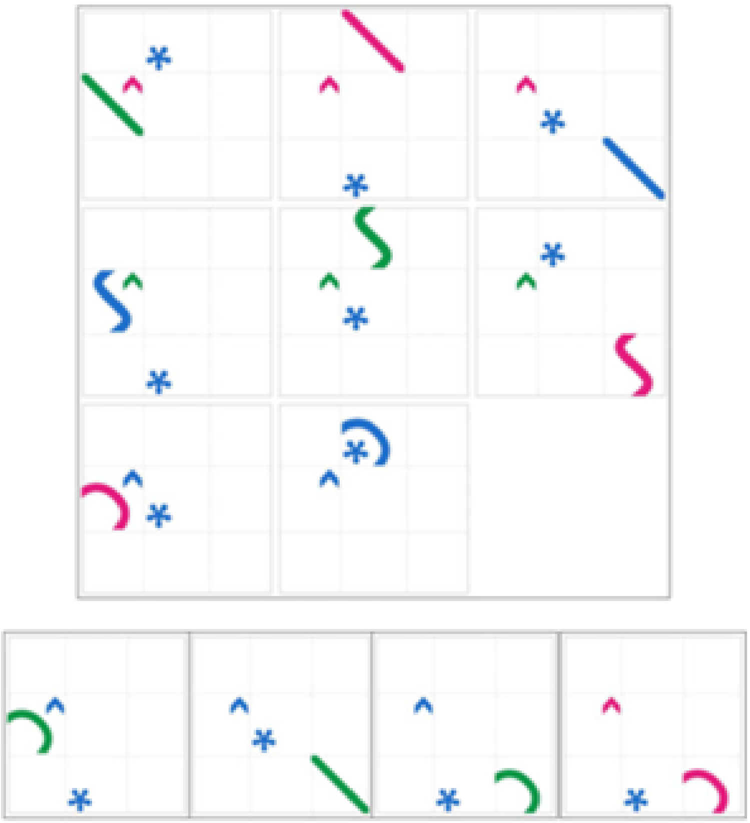

Figure 8. An incomplete matrix from the MaRs, to be completed by selecting one option from the 4 available below. To find the correct answer, the participant must infer the pattern of one or more shapes and its colors inside each square (e.g., the color and the position of the straight lines in the upper squares). This item is one of the more complex ones, involving interaction between different shapes and colors. In this case the third option from the left is the correct answer. Reprinted with permission from Chierchia et al (2019).

2.3. Measures

2.3.1. Coordination Games and Lottery

Considering previous similar studies (Chierchia et al., 2018; Chierchia, Tufano, et al., 2020; Chierchia & Coricelli, 2015), this study focused on four main dependent variables: Risk (UP choice probability), Switching (also referred to as trembling), Response Times (RT) and Payoff, with main priority given to the first 3 measures. As mentioned in the introduction, all these 3 measures are important in differentiating between cooperation and competition, therefore in exploring strategic ability. Furthermore, we treated as predictors the games (3 levels: cooperation, competition and lottery) and age, as a 3-level categorical variable (children, adolescents and adults).

2.3.1.1. Risk

Risky choices were coded as 1, if participants chose the risk option (UP), and 0, if they chose the safe option (SP).

2.3.1.2. Switching

We constructed our switching variable similarly to Chierchia et al. (2020), thus proceeding as follows: for each game, we first order the 15 trials in ascending order, based on the SP value; then, we dummy code each variant (with the exclusion of the first variant which by construction has 1 SP) with a ‘‘1’’ if the choice had changed relative to the previous variant, and with a ‘‘0’’ if it had not. Consequently, switching is the amount of switching from UP to SP (1 to 0) and vice versa across 15 trials for each game, also known as “Trembling” (Chierchia, Tufano, et al., 2020), which was found to be highly correlated with the measure of entropy (Chierchia et al., 2018) and often defined as uncertainty, or noise/randomness. In the same studies, participants usually chose UPs when the alternatives were lower SP values, and often switched to SPs when they became larger. In some cases, people might switch only once towards medium SP values (e.g., 7 or 8) in a perfect threshold strategy, although it is more often the case of multiple back and forth switching.

2.3.1.3. Response Times (RT)

The amount of time it takes for a participant to make a choice. Similarly to switching, this measure can be an indicator of lesser understanding and/or uncertainty, as well as greater impulsivity if RTs are low. Conversely, together with switching , RTs might represent an additional proxy for recursive reasoning in competition with increased response times in this condition compared to others (Chierchia et al., 2018) (Figure 4).

2.3.1.4. Payoff

This measure is intended to be a proxy for performance in different games, so how advantageous the participants' choices were, and it is calculated in the same way as Chierchia and colleagues (2018). In all conditions, the payoff of SP choices was simply the corresponding SP value, since it was always given when selected, while the payoff following UP choice depended on the condition. In the case of the ambiguous lottery, the amount awarded was always 7.5, i.e., the Expected Value considering an 50% probability to win the maximum prize (15), so 15*50/100.

In the cooperation condition, the expected value of the UP was calculated by multiplying 15, the potential winning, to the average of UP choice probability for the specific trial "x" excluding the participant "i" of which we are calculating the UP, thus considering the total number of participants minus one each time (e.g., if on average UP choice for the trial with SP= 3 is 0.7, the EV of the participant choosing UP in that trial is 15*0.7).

$$EV_{i(UP_x)}^{Coop} = 15 * \frac{\Sigma_{-i} UP(x)}{n-1}$$

In competition, on the other hand, the expected value of the UP is simply 15 times the inverse of the average of other people choosing the same option in the specific trial "x", since choosing the same options as others in this case is disadvantageous.

$$EV_{i(UP_x)}^{Comp} = 15 * \left(1 - \frac{\Sigma_{-i} UP(x)}{n-1}\right)$$

2.4. Procedure

Each age group was tested at different times and in different places, meaning that children and adolescents were in their respective IT classrooms, while adults were tested in the university with their own devices. Participants first completed a standard demographic survey and an informed consent form. Afterwards, with the aid of a PowerPoint presentation, an experimenter provided the instructions concerning the 3 games, the questionnaires and MaRs. The order of completion of each measure was the same for everyone, starting with the Pre-coordination questionnaire, then coordination games and lottery (in randomized blocks), followed by the post-coordination questionnaire and finally MaRs. The duration of the entire experiment varied from 30 to 40 minutes.

2.5. Statistical Analysis

To investigate differences between cooperation, competition and lottery across the three age categories, we started by calculating differences scores, or "deltas", of cooperation-competition on the three main dependent variables (risk, switch, RTs), with age as predictor (e.g., cooperation-competition for risk in adolescents, competition-lottery in switch in adults etc.). We performed ANOVA with the *car* package (J. Fox & Weisberg, 2019) to analyze main effect of the predictor age across deltas of risk, switching and RTs. In cases of significant main effect, we performed post-hoc analysis between deltas for each age category by computing estimated marginal means (EMMs) using the *emmeans* package (Lenth, 2023). This was done to assess whether deltas significantly differed from 0 for each age group, and thus to test for the ability to differentiate between games in children, adolescents and adults. Furthermore, we also investigated age differences in this ability by looking into pairwise comparisons between deltas belonging to each age group (e.g., how children risked in cooperation-competition compared to how adolescents and adults did). This procedure was repeated for each delta of the three main dependent variables, so delta cooperation-competition in risking, delta cooperation-competition in switching and cooperation-competition in RTs., thus involving 3 models. To investigate strategic ability, this work and its analyses mainly focus on social conditions (cooperation and competition); however, to verify the directionality regarding findings of greater cooperation or competition across the 3 main dependent variables and for each level of the age predictor, we have also analyzed scores differences of cooperation/competition and lottery (see Appendix for more details and results).

The 3 models above are the base models of interest. To these we added a number of control models. These include the base models but add, first in turn, and then all together, 7 additional predictors: gender, non-verbal reasoning (MaRs), comprehension (pre-coordination questionnaire), strategies (post-coordination questionnaire), risk-taking (total of UP choices in lottery, as a control for general risk behavior), and two models comprising “flagged” participants. In one model we removed participants who displayed a response time lower than 250ms and higher than 3 SD from the mean, to avoid potential effects of outliers on data analysis. In the second model, we flagged certain participants based on their choices in lottery that could suggest possible lack of understanding. To do so, we first excluded participants who never switched in lottery (always UP or SP choice), and then ran a Generalized Linear Mixed-Effects Model (GLMM) using the *lme4* package (Bates et al., 2015) which allowed us to extract slope coefficients of the series of 15 choices between SP and UP for each participant. Afterwards, we excluded participants with a slope coefficient greater than the 9^{th} quantile of the total, thus obtaining a list of participants who never switched from UP or SP (and vice versa) and/or displayed choice patterns suggesting lack of understanding. To look for age differences in the number of "flags" between the 3 age groups, we first ran a Kruskal-Wallis rank-sum test for main effects, and a Wilcoxon rank sum test with continuity correction for pairwise comparisons between age groups, both with the *stats* package (R Core Team, 2023). Additionally, we also "flagged" participants

Finally, to enquire whether control variables had an effect on age differences in cooperation-competition deltas, we ran a series of separate ANOVA and EMMs analysis for each of the dependent variable aforementioned, which included: gender, MaRs, Pre-coord questionnaire, post-coord questionnaire, amount of risking in lottery and exclusion of "flagged" participants. All data analyses were performed through *R-Studio* (RStudio Team, 2020).

3. Results

3.1. Descriptive Statistics

Descriptive statistics for the 4 measures across the 3 games are reported below (Table 2).

	Condition	Risk			Payoff			Switch			Reaction Time		
		Children	Adolescents	Adults	Children	Adolescents	Adults	Children	Adolescents	Adults	Children	Adolescents	Adults
Mean (SD)	**Cooperation**	0.55 (0.25)	0.49 (0.22)	0.66 (0.26)	9.04 (1.20)	9.32 (1.20)	11.15 (1.21)	0.31 (0.21)	0.28 (0.20)	0.13 (0.13)	2431.44 (1111.54)	2125.17 (1030.90)	2703.20 (1482.58)
	Competition	0.48 (0.23)	0.41 (0.18)	0.38 (0.18)	7.92 (0.61)	8.61 (0.38)	8.87 (0.54)	0.33 (0.19)	0.36 (0.19)	0.29 (0.18)	2451.02 (1141.72)	2263.26 (1152.09)	4155.20 (2761.65)
	Lottery	0.48 (0.22)	0.41 (0.19)	0.43 (0.17)	8.44 (0.74)	8.69 (0.71)	9.22 (0.57)	0.34 (0.18)	0.31 (0.19)	0.16 (0.13)	2578.16 (1400.55)	2080.75 (773.03)	2487.28 (1036.08)

Table 2. Descriptive statistics for each dependent variable (Risk, Payoff, Switch and Reaction Time) and each level of the two predictor variables (age category and condition), with means and standard deviations (in brackets).

3.2. Age-Related Differences in Strategic Ability

3.2.1. Risk

Delta cooperation-competition analyses revealed significantly greater risk in cooperation compared to competition for all age groups (all *ps* < 0.01), from small (for and adolescents and children) to large (for adults) positive effect sizes (Cohen's ds > 0.31, 95% CIs [>0.09, <1.45]) indicating that all three age groups chose the risky options more frequently in cooperation than competition. ANOVA showed a significant main effect of age (p < 0.001), while contrast analysis showed no significant difference between children and adolescents (p= 1.00), but significant difference between adults and the other two age groups (*ps* < 0.001) with large negative effect sizes (ds > -0.80, 95% CIs [>-1.00,>-0.60]), meaning that adults, compared to children and adolescents, risked more in cooperation compared to competition. Figure 9 contains plots visualizing risk choices across each trial, while Figure 10 summarizes results from this section and the following ones below.

3.2.2. Switching

Delta cooperation-competition analyses revealed significantly greater switching in competition compared to cooperation for adolescents and adults (all *ps* < 0.001), with negative effect sizes ranging from moderate (in adolescents) to large (in adults) (ds >-0.43, 95% CIs [>-1.03, <-0.20]), but not children (p = 0.42). This means that only adolescents and adults switched more frequently in competition compared to cooperation. Furthermore, ANOVA showed a significant main effect of age (p < 0.001), while contrast analysis showed significant differences between all groups (*ps* < 0.05), with positive small effect sizes for adolescents and adults/children comparisons and large for children-adults (ds > 0.30, 95% CI [>0.07,0.87]). This indicates that adolescents have switched more in competition than cooperation compared to children, who did not differentiate between the two, but less so compared to adults.

3.2.3. Response Times

Delta cooperation-competition analyses revealed significantly longer response times in competition compared to cooperation in adults only ($p < 0.001$), with large negative effect size (d= -0.83, 95% CI [-0.99, -0.66]), indicating that adults, but not adolescents and children, displayed longer RTs in competition compared to cooperation. ANOVA showed a significant main effect of age ($p < 0.001$), while contrast analysis of estimated marginal means showed no significant difference between children and adolescents ($p = 1.00$), but significant difference between adults and the other two age groups (*ps* < 0.001) with large positive effect sizes (ds > 0.69, 95% CIs [>0.48, <0.95]). This means that adults took longer to respond in competition compared to cooperation in comparison to children and adolescents.

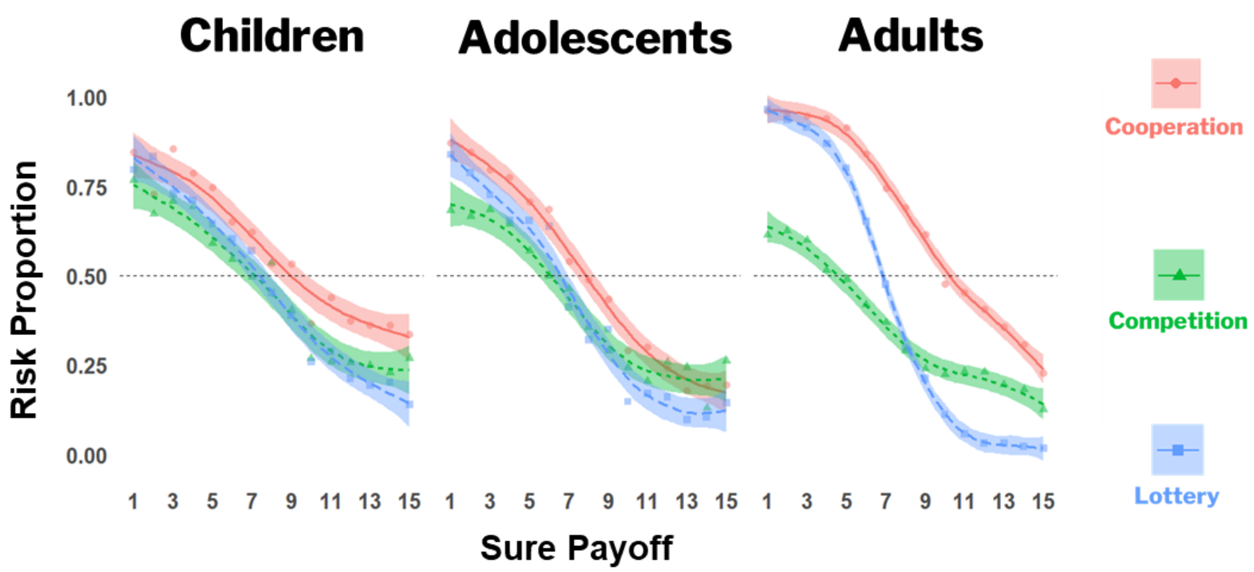

Figure 9. Similar trial-level plots to that of Chierchia et al. (2018) (Figure 2), showing the amount of UP choice (y-axis) for each SP value (x-axis) across the three age groups and conditions (represented by color and shape, with each point being an average of UP choices for that SP). Greater space between the lines indicates greater differentiation between conditions, which is highest in adults. Shaded ribbons represent 95% confidence intervals of the estimated fixed effects.

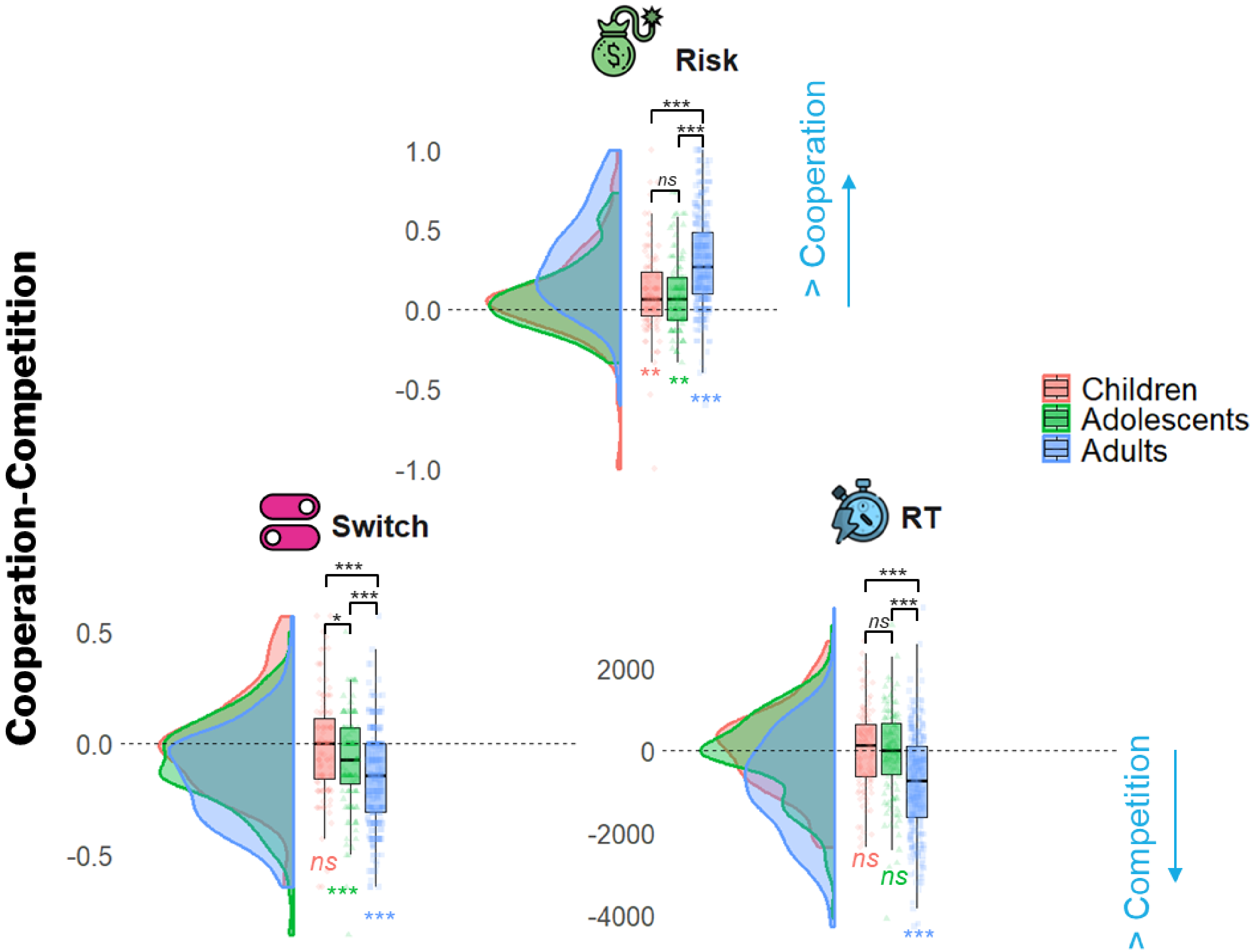

Figure 10. Raincloud plots (box + density plots) representing results for each of the 3 dependent variables' difference scores (or deltas, y-axis) between cooperation and competition for children (red), adolescents (green) and adults (blue), with a dashed line representing 0 (no differentiation between cooperation and competition). Each dot is a participant. The plots combine results from EMMs analysis for delta deviations from 0 (colored asterisks) and contrast analyses for age-related differences in cooperation-competition deltas (black squared brackets and asterisks). Upward arrows indicate positive values, thus greater cooperation, while downward arrows negative values and greater competition. Plots were obtained using the "raincloudplots" *R* package (Allen et al., 2021).

***p < 0.001, **p < 0.01, *p < 0.05, *ns*: p > 0.05

3.3. Age-Related Differences in Game Comprehension, Other-oriented Thinking and Non-Verbal Reasoning and Their Effect on Coordination Abilities

Each of our control variables varied significantly with age: ANOVAs revealed that adults understood the games more easily than children and adolescents (*ps* < 0.001, positive ds >0.94, 95% CIs [>0.74, <1.33]) (Figure 11), since they were also flagged to a lesser extent (*ps* < 0.01, with small positive effect size r > 0.14, 95% CIs [>0.04, <0.36]. Additionally, they obtained higher scores in non-verbal reasoning compared to younger age groups (all *ps* < 0.001, large negative ds <-1.65, 95% CIs [-1.88,-0.90]) (Figure 12), and also showed reduced egocentric biases in thinking about their own payoff as opposed to that of their interaction partners compared to adolescents (*p* = 0.02, d= -0.28, 95% CI [-0.48, -0.08]) (Figure 13). Importantly, each of these variables also predicted more risk taking in cooperation than competition (all *ps* < 0.001, $\eta^2 > 0.02$, 95% CIs [>0.01,<0.15]), but more switching and longer response times in competition than cooperation (all *ps* < 0.05, $\eta^2 > 0.01$, 95% CIs [>0.001,<0.12]) (Figures 10, 11 and 12). These findings strengthen the importance of controlling for these age-related variables, as done in the following control models.

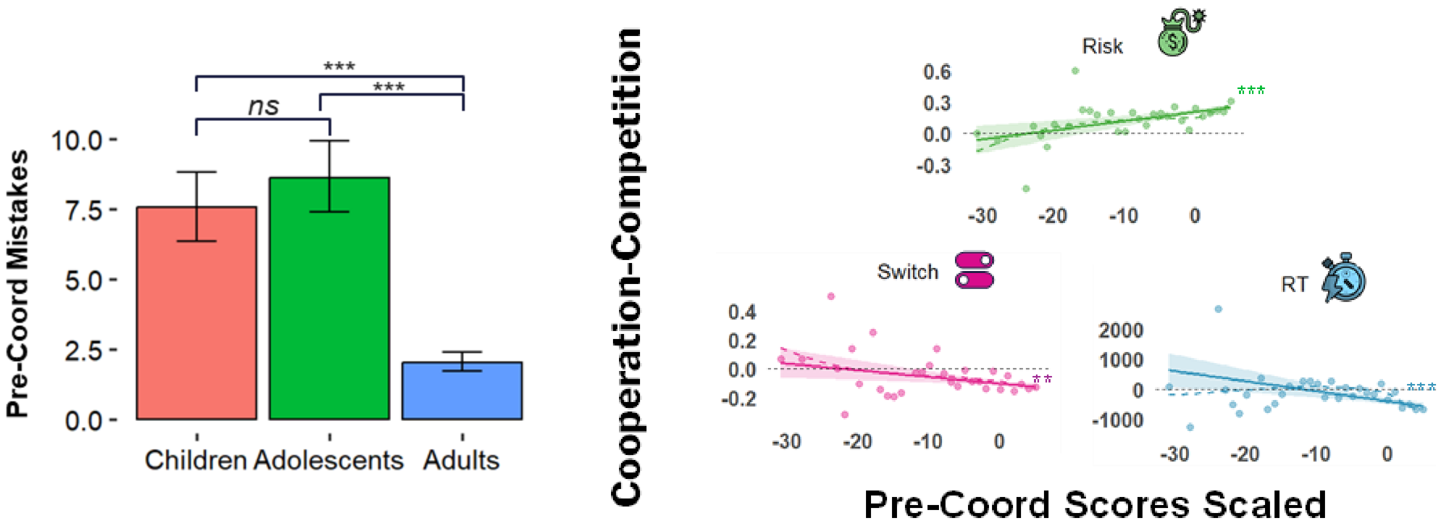

Figure 12. Left: age differences in the number of mistakes in the pre-coordination questionnaire, with higher values indicating lesser understanding. Right: linear models of pre-coordination scores (x-axis, mean centered across age groups and multiplied by -1 for clearer understanding) predicting the 3 dependent variables' deltas. Positive slopes indicate increased cooperation with greater comprehension, negative slopes indicate greater competition with increasing comprehension.

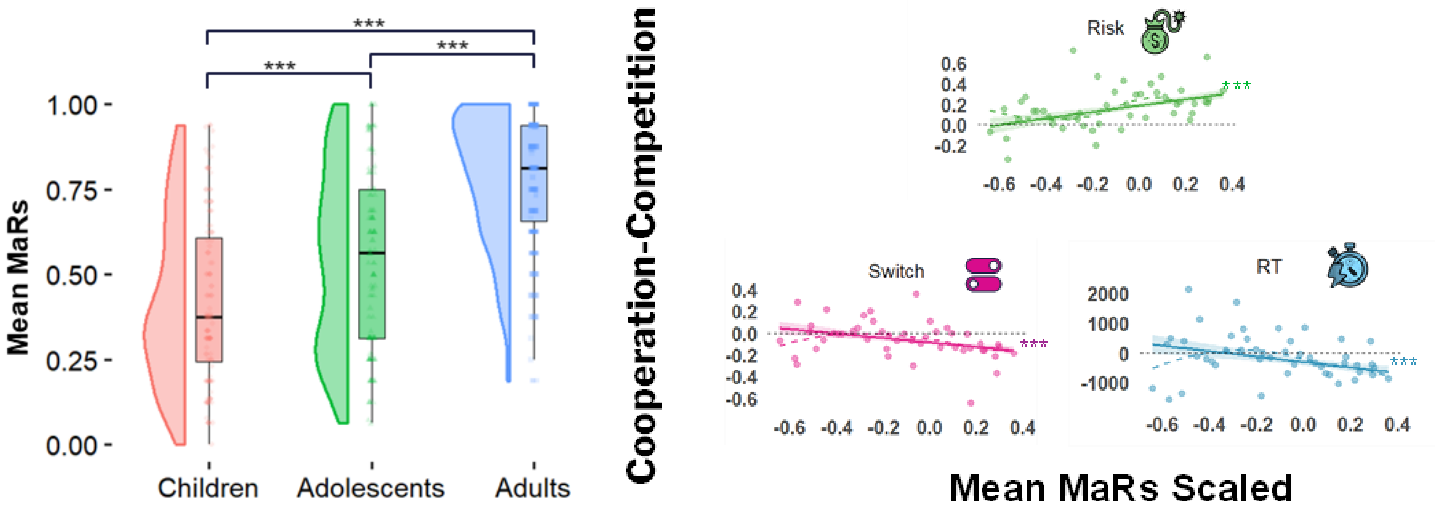

Figure 11. Left: age differences in non-verbal reasoning (mean of MaRs scores). Right: linear models of MaRs scores (x-axis, mean centered across age groups) predicting the 3 dependent variables' deltas. Positive slopes indicate increased cooperation with higher non-verbal reasoning, negative slopes indicate greater competition with increasing non-verbal reasoning.

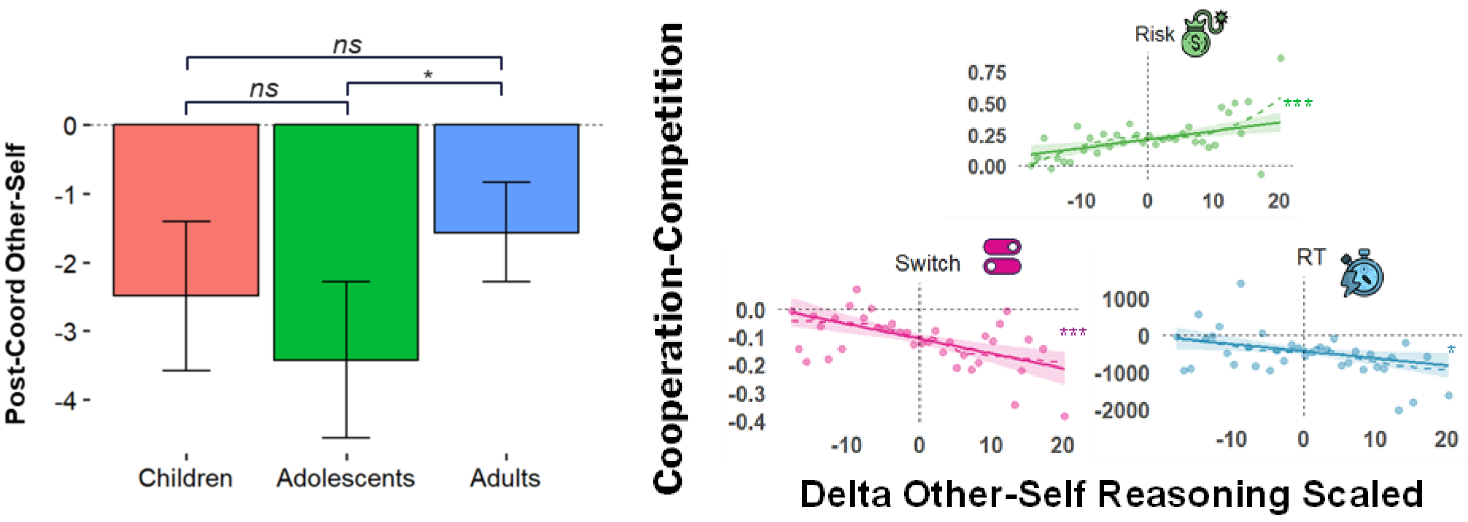

Figure 13. Left: age differences in egocentric bias, measured by the post-coordination questionnaire (other- self thinking scores). Right: linear models of other-self thinking deltas (x-axis, mean centered across age groups) predicting the 3 dependent variables' deltas. Positive slopes indicate increased cooperation with greater reasoning about others, negative slopes indicate greater competition with higher reasoning about others.

Finally, we re-ran the delta cooperation-competition analysis by adding one control variable each time (gender, pre-coord, post-coord, removed flagged participants, MaRs, lottery risk amount and all together) (Table 3). We continued to observe age differences between adults' and adolescents' coordination strategies when controlling for each of the control variables, with one exception: switching. Moreover, we found that age differences switching are cancelled by age-related differences in non-verbal reasoning (MaRs), and specifically between adolescents and children/adults (*ps* > 0.17).

Control Variables	**Risk**				**Switch**				**Reaction Time**			
	Control Main Effect	Children-Adolescents	Adolescents-Adults	Children-Adults	Control Main Effect	Children-Adolescents	Adolescents-Adults	Children-Adults	Control Main Effect	Children-Adolescents	Adolescents-Adults	Children-Adults
Default Model	/	*ns*	***	***	/	*	***	***	/	*ns*	***	***
Gender	*ns*	*ns*	***	***	*	*	***	***	*	*ns*	***	***
MaRs	*ns*	*ns*	***	***	*	*ns*	*ns*	**	*ns*	*ns*	***	***
Pre-Coord	*ns*	*ns*	***	***	*ns*	*	**	***	*ns*	*ns*	***	***
Post-Coord	***	*ns*	***	***	***	*	**	***	*	*ns*	***	***
Lottery Risk	*ns*	*ns*	***	***	*	*	**	***	*ns*	*ns*	***	***
Without Slope Flags	/	*ns*	***	***	/	*ns*	**	***	/	*ns*	***	***
Without RT Flags	/	*ns*	***	***	/	*	***	***	/	*ns*	***	***
All Covariates	/	*ns*	***	*	/	*ns*	*ns*	*	/	*ns*	***	***

Table 3. Multiple linear regression models of age differences across the 3 dependent variables, with each line representing a model with the formula DV~ Age Group (+ Covariate). Purple outline emphasizes the removal of age-related differences in switching between adolescents and children/adults after controlling for non-verbal reasoning (MaRs). ***p < 0.001, **p < 0.01, *p < 0.05, *ns*: p > 0.05

4. Discussion

4.1. Propensity for Cooperation and Aversion to Competition in Adolescence

In this study we provide evidence regarding the development of coordination abilities in diverse strategic contexts during adolescence, hypothesizing that they might emerge during this time. In order to examine these abilities, we investigated through coordination games whether adolescents improve in the ability to strategically coordinate their choices to those of other peers in cooperative and competitive environments without communicating, thus focusing on the development of strategic ability. Across three age groups between late childhood and early adulthood, analysis of strategic ability has shown that people of all ages took more risks in cooperation than competition. Importantly however, this propensity for cooperation increased with age, also leading to higher payoffs, which indicates that propensity for cooperation is adolescent developing and already present in children as young as 9-10.

Additionally, we found that adults displayed more response variance and longer response times under competition than cooperation, but only greater response variance in adolescents, indicating partial aversion to competition, as we did not find similar results for RTs. This suggests that, while propensity for cooperation is adolescent developing, aversion to competition is adolescent emergent. This pattern of results was also shown when comparing cooperation and competition to the non-social lottery, rather than to one another (see Appendix for details).

Furthermore, we controlled for an additional set of variables which could potentially explain age differences strategic ability, finding that age-related differences in aversion to competition, and specifically increased variance, were explained by improvements in non-verbal reasoning.

Previous studies by have highlighted a propensity for cooperation (C. Fox & Weber, 2002) and aversion to competition (C. Camerer, 1999) in coordination games in adults, as measured by greater risking in the cooperation, but also higher switching and response times in competition (Chierchia et al., 2018; Chierchia, Tufano, et al., 2020; Chierchia & Coricelli, 2015). The present study has replicated these findings regarding adults and has extended them to adolescents as well. Consequently, since we have confirmed these findings by considering lottery as well, our study shows once again that betting on others is not the same as betting against "Nature", and that the way we play against others highly depends on the strategic context as well. Furthermore, this phenomenon seems to be already present and increasing during adolescence.

Previously we discussed how adolescents become increasingly sensitive to their social context, and how they implement more strategically social cues from the environment (Güroğlu et al., 2014; Padilla-Walker et al., 2015; van de Groep et al., 2022): our results integrate this view with a developing ability to differentiate between strategic contexts, or strategic ability, which is still in earlier stages when competition is involved, especially given that age-related differences mainly concerned adults and children/adolescents, while children and adolescence only slightly differed in their choices variability in competition compared to other games. The presence in adolescence/late childhood of the ability to differentiate between social contexts (or betting on others) and non-social environments (betting on nature) is in line with findings of increasing ToM and sensitivity towards others mentioned above (paragraph 1.2.3). By this, we mean that, similarly to the findings of Fett et al., or Sijtsma and colleagues (respectively 2014; 2023), adolescents (and children) might be more willing to bet that others will risk along them in cooperation, reassured by the thought that they would think about the choices in a similar way, compared to simply being up against completely unknown chance in a lottery. As discussed by Chierchia et al. (2018), greater cooperation might be fostered by this prosocial belief since it would be reasonable to behave trustingly in the cooperation game, as it brings greater advantage to both. In addition to beliefs, the choices might also be driven by prosocial motives to trust others, not simply because it makes sense strategically, but also because of an inherent willingness to be trusting, which is more collectively beneficial (House et al., 2020). In competition, however, the same belief that others would behave similarly might render decisions more difficult, since in this case same choices bring to disadvantageous consequences, so in these circumstances decision-making might be more driven by social preferences. This leads to generally consider cooperation and competition as not simply diametrically opposite, but rather different, which might also be the reason why propensity for cooperation and aversion to competition might follow slightly different developmental schedules, since the former is present in children while the latter is only emerging in adolescence. Furthermore, risking, switching and RTs in competition and cooperation might be sensitive to different factors and to a different extent, which leads us to wonder which factors might be best suited to understand this differentiation and whether they might play a role in explaining age-related differences across these strategic contexts.

4.2. Possible Explanations for Age Differences in Coordination

Naturally, given the previously discussed results, the next step would be investigating some potential explanations regarding these age differences in propensity to cooperate and aversion to compete. To do so, we have taken into consideration 3 main candidates: comprehension (as measured by the pre-coordination questionnaire), non-verbal reasoning (MaRs average scores) and strategies (post-coordination questionnaire measures of thinking about the self vs. others). Indeed, given the development of socio-cognitive abilities during adolescence (e.g., Choudhury et al., 2006; Dumontheil, Apperly, et al., 2010; Hartung et al., 2020), it is reasonable to look into age-related differences in strategic behavior by taking into account cognitive and social factors, the former more represented by comprehension and non-verbal reasoning, while the latter perhaps better exemplified by self-reported strategies given the involvement of thinking about the other counterparts while making decisions. Moreover, all three measures proved to be sensitive to age, generally reflecting cognitive improvements and more social strategic balance for older participant: not only, but they were all also associated with propensity to cooperation and aversion to competition regardless of age.

Once we have shown that these 3 predictors have an effect on cooperation and competition in general, we asked ourselves whether we might continue to observe effects of age when controlling for them. Indeed, that seems to be the case for Risk and RTs where we keep observing differences between adults and children/adolescents but not between adolescents and children, whereas surprisingly the age differences in switching between adolescents and adults were cancelled out by age differences in non-verbal reasoning only. In simpler terms, adults might switch more in competition compared to cooperation because of more developed reasoning abilities, rather than simply due to higher chronological age. This might be due to the previously mentioned link between switching in competition and strategical/hierarchical reasoning theorized by Chong et al. (2005) and hypothesized by Chierchia and colleagues (2018) to be behind differences in cooperative and competitive contexts. Specifically, greater effort in thinking what the anonymous counterpart might think about us thinking about him/her in a recursive manner might lead one to frequently switch from a SP to a UP, in the attempt to anticipate the other person's choices and avoid choosing the UP at the same time. This same process might not be engaged as much in cooperation, since it could be enough stopping at a more basic level of strategic thinking to make the optimal choice, i.e., it might suffice to think about the other person's probable first choice rather than recursively attempting to predict their thoughts.

It is also the case, however, that the same amount of switching might be a sign of increased reasoning in one case, but also higher noise (entropy) in another, thus a product of either better or worse understanding. Indeed, we did not find in adolescents longer RTs in competition compared to cooperation (and lottery) to further corroborate greater inferential effort, as we did in adults, and neither the removal of age-related differences in RTs when controlling for non-verbal reasoning. Adolescents have often been portrayed as noisier or more uncertain (Reiter et al., 2021), so greater switching without longer response times might point towards the same direction. Nonetheless, switching conceptualized as entirely noise does not explain the involvement of non-verbal reasoning in competition, which ultimately might suggest that switching in competition only is more sensitive to strategic reasoning, which might especially emerge during adolescence, thus partly explaining age related differences in competition aversion.

Although the name strategic or hierarchical reasoning might suggest fairly “cold” cognitive abilities, the recursion involved in it is typical of social contexts, since mental states are distinguished by physical states also by the fact that they can be recursive, seeing as the people we trying to understand possess thoughts of their own about us. Together with the previously mentioned propensity to cooperate, the age-related differences of strategic reasoning underlying switching in competition might be indirectly indicative of an increased sensitivity to others and their intentions during adolescence (e.g., Dumontheil, Apperly, et al., 2010; Sul et al., 2017; van den Bos et al., 2011). Nevertheless, this behavioral indicator of possible other-oriented thinking is not yet paralleled by a greater self-reported balance between thinking about own and other people’s choices, which likely emerges in late adolescence. Indeed, adults have overall thought about the goals of their anonymous counterparts significantly more than children and adolescents, while all age groups kept their own aims in mind.

4.3. Adolescence and Risk: Between Impulsivity and Strategy

In the process mentioning risk in the last few paragraphs, we have frequently discussed about it in terms of propensity for cooperation, while taking for granted a crucial finding which warrants a deeper discussion: adolescents did not engage in indiscriminate risk-taking behavior and were not always the greatest risk-taking age group. Regarding the first assessment, evidence from maturational imbalance or dual models (Casey et al., 2008; Steinberg et al., 2018), might lead us to hypothesize that greater motivational sensation-seeking could result in adolescents always risking more without showing particular preferences towards cooperation or competition. Similarly, but from a different point of view, alternative theories such as the life span wisdom model (Romer et al., 2017) could predict greater exploration tendencies throughout the various games, which might appear as greater general risk-taking . In contrast to this, we found that adolescents adapted their risk-taking behavior based on the strategic context they were in, which was also beneficial in terms of payoff, thus showing the ability to be mindful of the circumstances and consider the best course of action. We did, however, find that children and adolescents not only made more mistakes than adults in the pre-coordination questionnaire (comprehension), but also frequently and repeatedly chose the same incorrect answer, which can be interpreted as greater impulsivity. Nonetheless, adolescents also risked less than adults in cooperation (compared to competition and lottery), which is unlikely due to greater sensation-seeking in adults compared to adolescents given the developmental trajectories (Steinberg et al., 2018), but possibly due an increasing (but not yet mature) capability to understand the type of strategic context and opt for the more collectively advantageous choice.

Taken together, the findings regarding selectively greater switching in competition and higher risk-taking in cooperation in adults compared to younger age groups suggest that this type of behavior is also modulated by the strategic context. This has potential implications in the way certain assessments regarding adolescents are made, especially in terms of how findings regarding risk-taking or “noise” are generalized. Additionally, in the introduction (paragraph 1.2.4) we discussed how risk-taking behavior might change depending on the social context (Molleman et al., 2022) as well: this is also true for the emotional context, since Figner and colleagues (2009) found that adolescents were more likely to risk compared to adults in context that were more affectively engaging, while displaying no difference in more deliberate, or “colder” circumstances. In addition to social and emotional contexts, adolescent’s risk-taking behavior has been shown to depend also on whether the individual has access to the probability of an outcome or not (Tymula et al., 2012), wherein adolescents were more risk tolerant towards ambiguity (unknown probability) and risk-averse when probabilities were known compared to adults. With this work, we integrate this evidence by arguing that risk-taking in adolescence also depends on the strategic context, proving to be greater in cooperation similarly to adults, although to a lesser extent. Ultimately, the argument that adolescents are increasingly strategic might be against stereotypical views of adolescence as an age of “storm and stress” (Buchanan & Bruton, 2016), and could give more credit to adolescents’ decision-making abilities, thus perhaps providing some evidence against greater lack of responsibility during this years.

4.4. Adolescence as a Sensitive Age for The Development of Strategic Abilities

In the previous sections (paragraph 1.2.4) we have discussed evidence in favor of the hypothesis that adolescence might represent a second sensitive period of development (Fuhrmann et al., 2015). Specifically, recent evidence shows protracted brain changes during adolescence in terms, with a particular focus on peak brain variability (Bethlehem et al., 2022), increased neuroplasticity (Petanjek et al., 2011) and cognitive development (Choudhury et al., 2006; Hartung et al., 2020), but also heightened sensitivity to peer influence (e.g., Chein et al., 2011; Gardner & Steinberg, 2005; Reiter et al., 2021). These changes take place during a time of marked social re-orientation (E. E. Nelson et al., 2005) and exploration of unfamiliar environments (Ciranka & van den Bos, 2021), which might foster the emergence of more complex social behavior. Indeed, adolescents become increasingly coordinated to their social environment by becoming more sensitive to the peers they are playing with or against (Gummerum et al., 2020; Sijtsma et al., 2023; Westhoff et al., 2020): our findings extend these considerations of improving coordination to strategic environments as well, given the developing propensity towards cooperation and aversion to competition, which is also related to improvements in non-verbal reasoning. In other words, adolescents are not only becoming increasingly sensitive to the attitudes or characteristics of the counterparts they are interacting with, but also to the environment they are interacting in, by managing to understand more advantageous courses of action in relation to other people's choices.

Furthermore, the emergence of strategic coordination might represent an important milestone in social development, since it might help bridge the gap between self- and other-interest, and thus foster better social integration. Indeed, ongoing work

(Stagnitto et al., in prep) shows that coordination games are associated with peer relationships as measured by peer nominations (i.e., indices of how liked or disliked a peer is among their classmates). Specifically, it seems that competition, but not cooperation, is sensitive peer relationships, in the sense that least liked adolescents compete more (higher risk) and do so less flexibly (less switching). This has two implications, one more theoretical and a second relatively practical: firstly, these results again show that cooperation and competition are not simply opposites, but different (as discussed above), since competition was sensitive to peer nominations, but cooperation was not; secondly, we have reason to believe that these coordination games might be more than strictly strategic games, since they have links to real-life. To further expand this last consideration, the ongoing work by Stagnitto and colleagues is also finding some associations between coordination games and Theory of Mind measures (i.e., Silent Films and Strange Stories; Devine & Hughes, 2013; Happé, 1994), in terms of negative correlations between risking in competition and ToM scores.

Finally, the increasing ability to coordinate with others in strategic contexts, and its real-life implications might represent additional evidence in considering adolescence as a second developmental sensitive period. Indeed, since we argue that this ability might be potentially useful in solving social dilemmas and integrating into a peer-focused environment, cases in which its development might be delayed or hindered could be characterized by more maladaptive social behavior, similarly to how early childhood experiences might play a part in later psychopathologies (Green et al., 2010; C. A. Nelson & Gabard-Durnam, 2020). In the future, for instance, studies involving neurodivergent participants (which are underway), might shed more light on the relationship between strategic social coordination and ToM or general aspects of social cognition and behavior.

5. Limitations

This study presents some limitations which need to be addressed. To begin with, age was considered and analyzed in terms of groups, and thus treated as a 3 factors predictor variable, which might decrease statistical power and lead to less reliable results. This is due to the fact that initially we only had two age groups, adolescents and adults, which were only later joined by children, and because of a 3-year age gap between adolescents and adults. Naturally, the next step would be re-analyzing the data with age as a continuous variable, with due caution regarding the interpretation of results given the age gap, which could also be solved by recruiting additional high-school participants. Indeed, late adolescents might yield clearer results in terms of aversion to competition, which was only partial in our sample.

Although our sample size was large (N= 596), young adults (N= 299) were mostly female (81%), which is likely given by the fact that the adults were entirely students from the Bachelor of Psychology of the University of Pavia, which is predominantly attended by women. Together with the fact that this was a convenience sample, this might hinder the generalization of our results, which future studies could improve by recruiting a more balanced sample.

Regarding the measure of non-verbal reasoning, initially we used a MaRs version with the same level of difficulty for children, adolescents and adults, which proved to be perhaps too easy for the latter, given the evidence for ceiling effects. This might confound results regarding age-related differences between adolescents and adults in switching driven by non-verbal reasoning.

Although coordination games allow to quantify social strategic behavior across different contexts fairly reliably, they possess little explanatory power behind people’s choices across different measures (mainly risk, switching and RTs), which we have tried to integrate by looking into additional measures. To obtain additional valuable information and fully harness the potential of these tasks, future steps could involve employing computational modelling, i.e., computerized simulations of people's decisions. Indeed, this method could provide more refined and deeper insights into coordination abilities, since it allows the implementation of parameters such as altruism, beliefs, reasoning etc., to understand more effectively which factor could better predict people's choices across age and how the contribution of that factor might change with development, similarly to what Sul and colleagues did in their study (2017).

Finally, we consider the answers provided by this study as a potential starting point for many other questions. Once established that adolescence is also an age of increasing strategic (in addition to social) coordination with others, we can ask ourselves how individual differences in this ability might affect different aspects of our lives, such as social relationships, work- or school-related achievement and mental health, to name a few, but also how we can improve it. Answering these questions might help us better understand what lies behind our aptitude to coordinate with others and, to some extent, what sets us apart from other species.

6. Conclusion

Our results showed that propensity for cooperation – the tendency to risk more in cooperative environments than competitive or non-social environments – is already present in late childhood but increases markedly during adolescence. It is thus adolescent developing. In contrast, aversion to competition – the tendency to display more response variability and longer decision times in competitive environments relative to cooperative or non-social environments – is not observed children, is partly observed in adolescents and is clearly displayed by adults. It is thus adolescent emergent. We also find that that aversion to competition, but not propensity for cooperation is partly explained by age-related improvements in non-verbal reasoning ability. During an age in which people increasingly interact with their peers as opposed to their caregivers, these results reveal a new hallmark of adolescent social re-orientation: adolescence could be a sensitive age for the development of strategic abilities. Overall, by charting how different strategic abilities change during human development, this work provides new measures to track normal and atypical social development. It also sheds light on which ages might be more malleable to interventions aiming to improve social abilities during late childhood and adolescence, subsequently promoting individual well-being, as well as a more cooperative community.

7. Appendices

All the supplementary material, including R code, anonymized data and supplementary plots and analyses are available in a GitHub repository.

8. Bibliography

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