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Probability errors in adults' and children's decision-making

Dean A. Marshall [a,*], Elizabeth Meins [b]

[a] School of Psychology, Liverpool John Moores University, Liverpool, UK
[b] Department of Psychology, University of York, York, UK

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ABSTRACT

Three studies evaluated Tversky and Kahneman's (1983) proposal that the conjunction fallacy (judging the probability of a conjunction of two events to be higher than that of its component events) arises due to the representativeness heuristic. Since such heuristic thinking is not innate and depends upon the individual learning the extent to which situations are likely to occur, our evaluation adopted a developmental approach. Study 1 ($N = 82$ adults; $N = 71$ 4- to 5-year-olds), Study 2 ($N = 130$ adults; $N = 148$ 4- to 11-year-olds), and Study 3 ($N = 76$ adults) assessed objective probability judgements by asking participants to determine whether a single player or a two-player team would win based on assigned poker chip (adults) or building block (children) distributions. Social judgements were based on descriptions of individuals. All three studies showed that adults' conjunction fallacies in objective probability judgements were (a) influenced by the likelihood of winning, and (b) positively correlated with conjunction fallacies in judging social characteristics. Children's conjunction fallacies in objective probability judgements were not influenced by manipulating the probabilities assigned to either team, and did not differ as a function of children's age. Fallacies on the objective and social judgement tasks were positively correlated in 10- and 11-year-olds, but not in younger children. Study 3 showed a "thinking aloud" procedure (to facilitate rational, non-heuristic decision-making) reduced adults' fallacies on the social judgement, but not the objective probability task. Findings are discussed in relation to developmental changes in decision-making, and common versus distinct cognitive processes associated with objective and social judgement errors.

Human decision-making is notoriously prone to errors, and we are particularly subject to poor reasoning when required to evaluate statistical probabilities. Unlike a decision based on personal opinion, decisions based on probabilities can objectively be judged to be correct or incorrect on the basis of whether they violate the rules of probability (Mazur, Hickam, Mazur, & Mazur, 2005). Tversky and Kahneman (1983) described a particular error, in which the probability of a conjunction of two events is judged to be higher than that of its component events in isolation. These errors violate the conjunction rule, according to which the probability that A and B are both true [P(A&B)] can never exceed the probability of A being true [P(A)] or the probability of B being true [P(B)], because [P(A&B)] is calculated by multiplying [P(A)] by [P(B)] (Howson & Urbach, 1991). The conjunction rule can be illustrated in terms of judging the likelihood of drawing different playing cards from a standard deck whereby the probability of drawing a red queen (defined by two features) is lower than the probability of drawing either a red card or a queen. Violations of the conjunction rule are known as the conjunction fallacy.

Although these errors tend to be rare on judgements about the probabilities of drawing particular cards from a deck, they are more common when we make other types of probabilistic judgements. Errors in objective judgements can be assessed using vignettes involving poker chips, where the only background information provided is a set of objective numbers split to represent a component (a single player) and a conjunction (a team of two players); participants can therefore calculate mathematically the actual probabilities of the events occurring. For example, participants are told that the single player and one person on the two-player team each have two blue and eight red chips in their bags; the other person on the two-player team has eight blue chips and two red chips. To win the game, the single player must draw a blue chip from their bag, but for the two-player team to win, both must draw a blue chip. The proportion of blue chips in the single player's bag can be varied so that sometimes the probability of drawing the designated color is unlikely (as in the example above) or likely (e.g., eight blue chips and two red chips in the example above). Fisk and Slattery (2005) reported that 9 % of adults stated that the two-player team would win (and thus

* Corresponding author.
E-mail address: d.a.marshall@ljmu.ac.uk (D.A. Marshall).

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made the conjunction fallacy) for the likely-to-win single player condition, and 29 % of adults made this error for the unlikely-to-win single player condition. Some adults thus make the conjunction fallacy even when they are provided with objective information from which they can calculate actual probabilities. While these findings suggest that the probability assigned to the single player in these tasks influences the conjunction fallacy rate, research has not investigated how manipulating the probabilities assigned to each person on the two-player team (and thus to the two components of the conjunction) relates to the likelihood of individuals making these errors.

Conjunction fallacies are even more common when adults make judgements about individuals' social characteristics. In their seminal research, Tversky and Kahneman (1983) provided participants with some brief background information on an individual and then asked them to rank a number of statements from most to least likely with regard to that individual. The background information was consistent with some of the statements more than others, and the statements crucially contained one involving a conjunction between a likely and unlikely statement. For example, having been provided with information describing Bill's rather boring personality, the statements to be ranked included "Bill is an accountant" (deemed likely), "Bill plays jazz for a hobby" (deemed unlikely), and the conjunction of these statements: "Bill is an accountant who plays jazz for a hobby". As explained above, the probability of a conjunction can never be higher than the probability of either of its components because multiplying the probabilities of the two components will always result in a value that is lower than the probability of the components in isolation. Nevertheless, Tversky and Kahneman reported that 87 % of their participants ranked the conjunction higher than the statement "Bill plays jazz for a hobby", and thus committed the conjunction fallacy.

Conjunction problems functionally equivalent to those used by Tversky and Kahneman (1983) can be presented in varying formats, and the presentation format changes the rate of fallacy errors. For example, when participants were asked to rate the likelihood between 0 and 100 of the conjunction and its components (i.e., a direct probabilistic judgement, rather than ranking), 70 % assigned a higher probability to the conjunction than to either or both of its component statements (Tversky & Koehler, 1994). When the conjunction problem is presented in a frequency format (e.g., Imagine 100 people who match the description of Bill; of these 100, how many do you think are accountants, how many do you think play jazz for a hobby, how many do you think are accountants and play jazz for a hobby?), the reported incidence of the conjunction fallacy is substantially lower, but nevertheless, it is committed by almost a quarter (22 %) of participants (Fiedler, 1988). The problem as summed up by Gould (1992) is that "our minds are not built (for whatever reason) to work by the rules of probability" (p. 469).

The extant literature thus provides consistent and substantial evidence for conjunction fallacies in both objective and social judgement tasks, but much less is known about why these decision-making errors occur. Tversky and Kahneman (1983) attributed conjunction fallacies to the representativeness heuristic. The premise of this heuristic is judging the likelihood of a variable by how much it matches a category of traits (Kahneman & Tversky, 1972). The representativeness heuristic is often very useful in everyday life—we assume that the person dressed in a police uniform is a police officer, that the person wearing an apron in the restaurant is a waiter, and so on (Shepperd & Koch, 2005)—but it can also lead to us making conjunction fallacies. Yates and Carlson (1986) proposed that the conjunction fallacy is most common when one component is deemed highly likely (representative) and the other highly unlikely (unrepresentative), meaning that the component probability differentials are large. For example, if participants are told that a man has unusual tastes, is married to a performer, and has multiple tattoos, they are more likely to assign a higher probability to him being a trapeze artist than a lawyer or librarian, despite the fact that the latter two occupations are statistically (i.e., objectively) more likely (Swinkels, 2003). This error comes from ignoring the base rate probability of those occupations, and instead basing probability judgements on the description being representative of a trapeze artist and not of either a lawyer or a librarian. Other researchers have discussed how the representativeness heuristic could also help explain errors on objective decision-making tasks, such as the poker chip task. For example, Fisk and Slattery (2005) argued that likely probabilities are perceived to be representative, whereas unlikely probabilities are perceived as unrepresentative. This argument was used to explain their finding that the conjunction fallacy was more likely to occur in the standard poker chip task when the single player was assigned a probability that was unlikely rather than likely to win.

The three studies reported here evaluated Tversky and Kahneman's (1983) proposal that conjunction fallacies arise due to a reliance on the representativeness heuristic. First, all three studies used the poker chip task to investigate whether manipulating the probability of winning assigned to the two-player team affected the conjunction fallacy rate. If this error is governed by the representativeness heuristic, the probability that is likely to win (i.e., representative) should influence proneness to the conjunction fallacy, regardless of which player is assigned this likely probability.

Second, if the representativeness heuristic underlies conjunction fallacies on both objective and social judgement tasks, one would expect errors on these two types of task to be positively related. Surprisingly, no study has yet investigated the relation between conjunction fallacies on objective and social judgement tasks. However, while it may be the case that individuals who have a poorer grasp of the mathematical rules of probability will also be more prone to probability errors when judging the likelihood of social characteristics, the large discrepancy in conjunction fallacy rates between objective and social judgement tasks suggests that factors other than mathematical understanding of probability are involved in social conjunction fallacies. The size of any positive correlation between conjunction fallacies on objective and social decision-making tasks may therefore be modest. The three studies reported here investigated this question.

Third, if reliance on the representativeness heuristic is responsible for conjunction fallacies, then these errors should relate to the types of cognitive processes associated with quick decision-making. Dual process theories of cognition describe two different and often competing thinking systems (Kahneman, 2002, 2011). Type 1 (sometimes called System 1, heuristic, or fast thinking) is almost instantaneous and relies heavily on prior knowledge for top-down problem solving (Kahneman & Frederick, 2002). Type 2 (sometimes called System 2, analytical, or slow thinking), is a slower, bottom-up, more deliberate process which applies rationality and logic (De Neys & Glumicic, 2008). It is widely accepted that Type 1 thinking is automatic—the default mode for quick decision-making which is often (but not always) correct. The asymmetry in time and effort taken to use Type 1 and Type 2 processes has been used in a number of studies to account for reasoning errors, such as base rate neglect and belief bias (Evans & Curtis-Holmes, 2005; Thompson, Turner, & Pennycook, 2011). However, previous research has not investigated whether Type 1 thinking is associated with the conjunction fallacy. If heuristic thinking is indeed responsible for the conjunction fallacy, one would hypothesize that encouraging individuals to slow down their thinking processes would result in a decrease in these errors. Study 3 investigated this hypothesis.

Finally, we adopted a developmental approach to investigate the role of the representativeness heuristic in determining the conjunction fallacy. Clearly, this heuristic is not innate and depends upon the individual learning the extent to which situations are likely or unlikely to occur. While adults are frequently required to make judgements based on probabilities in various aspects of their lives, children also encounter situations that prompt them to consider the comparative probabilities of different events occurring. For example, children may judge the likelihood of conjunctions such as going shopping and getting a treat, and realize that this is less likely than the probability merely of going shopping. If the representativeness heuristic underlies the conjunction fallacy, and this heuristic is acquired via experience, one might predict that younger children will be less prone than older children and adults to this error. Previous research lends some support to this proposal.

Davidson (1995) modelled her procedure on Tversky and Kahneman's (1983) adult task, giving children a short description meant to represent an elderly person and asking them to rate the likelihood of a series of statements, one of which was a conjunction between a likely and unlikely component. Davidson found a progressive increase in conjunction fallacies between the ages of 7 and 12, and attributed this to children's increased reliance on the representativeness heuristic as they get older. Gualtieri and Denison (2018) investigated the extent to which decision-making is influenced by background information, comparing 4- to 6-year-olds with adults. Their findings indicate that use of the representativeness heuristic increases between 4 and 6 years of age, with the performance of 6-year-olds being similar to that of adults. These older children and adults tended to ignore base rate probabilities in favor of using background information in making their judgements, even when the information provided was not relevant (Gualtieri & Finn, 2022). Marshall and Meins (2024) investigated children's social judgement conjunction fallacies across three separate studies. Their findings suggested that children make conjunction fallacies at chance level until they reach age 10. By this age, children's pattern of errors was similar to that in a sample of adults: adults and 10- and 11-year-olds were significantly more likely to make conjunction fallacies after they had been provided with background information about the vignette characters, but the conjunction fallacy rate in younger children was not influenced by the introduction of background information.

One study has investigated children's tendency to commit the conjunction fallacy when making objective probability judgements. Fisk and Slattery (2005) developed a task modelled on the poker chip procedure that was suitable for young children. Three teddies were divided into two teams and children were asked to judge which team was more likely to win a game where each teddy had to randomly draw out a brick of a particular color from their respective tubs, with the probability of the single player winning being manipulated, as in the adult poker chip task. Fisk and Slattery reported that 41 % of 4- to 5-year-olds and 38 % of 8- to 9-year-olds made the conjunction fallacy in the likely single player condition, and 61 % of the younger and 64 % of the older children made the error in the unlikely single player condition. There was therefore no age-related difference in children's tendency to make conjunction fallacies. The pattern observed in both age groups of children mirrors that seen in the adult participants, with a higher error rate when comparing the unlikely-to-win single player than the single player likely-to-win condition, but error rates in both types of judgement were considerably higher in children than in adults (adult error rate of 29 % and 9 % for the respective conditions). In contrast to the developmental literature on social judgements, Fisk and Slattery's results thus do not show that children are less likely than adults to make the conjunction fallacy, and are therefore not in line with the proposal that the development of the representativeness heuristic is responsible for these errors. However, without replication, it is difficult to draw strong conclusions from these findings.

As is the case in the adult literature, no study has investigated whether children's tendency to make the conjunction fallacy on an objective probability judgement task relates to their proneness to this error when judging people's social characteristics. Given the different pattern of findings reported in the extant literature for children's conjunction fallacies on social versus objective tasks, one might expect these errors on the two different types of task to be unrelated early in development, but to become positively correlated in older children. Such a developmental change would indicate that the same underlying cognitive mechanism—potentially automatic reliance on the representativeness heuristic—increasingly comes to govern individuals' tendency to commit conjunction fallacies.

The overarching aim of the three studies reported here was to evaluate the evidence for the representativeness heuristic being responsible for conjunction fallacies across different developmental periods. To achieve this aim, we investigated (a) how the individual probabilities assigned to the players in objective decision-making tasks relate to the conjunction fallacy rate, (b) how conjunction fallacies on objective decision-making tasks relate to these errors on social decision-making tasks, (c) how (a) and (b) vary across development, and (d) whether Type 1 thinking processes may help explain why adults make conjunction fallacies. The studies were preregistered on the Open Science Framework (https://osf.io/j3zfs/?view_only=42bf1917b8364108bb3a79ac14fecc4c), and data from the studies are available via this platform.

1. Study 1

The first aim of Study 1 was to investigate whether changes in the design of the objective decision-making task influenced adults' and children's tendency to make conjunction fallacies. Recall that Fisk and Slattery (2005) reported that manipulating the probability of the single player winning had an impact on the rate of conjunction fallacies, with both adults and children being more likely to judge that the two-player team would win in the condition where the probability of the single player winning was low compared with high. These findings suggest that decisions are influenced by the probability of the single player winning, but research has not yet investigated whether the probability assigned to the second player in the two-player team plays a role in causing the conjunction error. In Study 1, we explored how manipulating the probabilities assigned to the two-player team related to the conjunction fallacy rate. We hypothesized that the fallacy rate would be highest when one of the players in the two-player team had a high probability of winning, and the single player had a low probability of winning. Study 1 investigated whether both adults and young children were sensitive to manipulations in the probabilities assigned to the two-player team. In addition to investigating how the two-player team's probabilities related to the conjunction fallacy rate, we expected to replicate Fisk and Slattery's findings with regard to manipulating the probability assigned to the single player. A higher fallacy rate when the single player was assigned a low versus high probability of winning was therefore predicted.

The second aim of Study 1 was to investigate how conjunction fallacies on the objective decision-making task related to these errors when making judgements about people's social characteristics. It seems likely that there will be some common underlying cognitive processes in making both objective and social judgements, but as discussed above, conjunction fallacy rates are substantially higher when making judgements about people's characteristics than when judging the probabilities of poker chips. We therefore predicted that adults' conjunction fallacies on objective and social decision-making tasks would be positively correlated, but expected the size of this relation to be modest. Study 1 explored whether this pattern was also observed in children. It may be the case that young children rely on the same decision-making processes in judging objective probabilities and social characteristics, in which case a positive association between conjunction fallacies on both types of task would be expected. However, Marshall and Meins (2024) reported no associations between children's conjunction fallacies in judging social characteristics and core cognitive and social-cognitive abilities such as language and theory of mind. These null findings contrast with the positive associations reported between these core abilities and other types of decision-making (e.g., Frith & Singer, 2008; Zelazo, Muller, Frye, & Marcovitch, 2003). Consequently, young children may approach objective and social decision-making tasks in very different ways, and conjunction fallacies on the two types of task may be unrelated. We therefore did not make a directional hypothesis for the relation between errors on the objective and social decision-making tasks in children.

2. Method

2.1. Participants

A total of 82 psychology undergraduate students (69 women, 13 men; 70 White, nine Asian, three Black; age $M = 19.4$ years, $SD = 1.38$, range 18–26) volunteered via an online participant recruitment website. Participants received course credit for their participation. The 71 child participants (39 girls, 32 boys; 63 White, seven Asian, one Black; age $M = 57.9$ months, $SD = 3.84$ months, range 48–66) were recruited from three schools in North-West England. Teachers reported that no child had any diagnosed learning or neurological disorder. Children were given stickers both during testing as an incentive, and a bag of stickers to take home as a reward. The adult and child samples were appropriately powered to detect small to medium effects for binomial and correlational analyses (power > 0.84). The study was approved by the relevant University Ethics Committee, and data were gathered in accordance with the ethical code of practice of the British Psychological Society and fully complied with the Data Protection Act 1998. Fully informed written consent was obtained for all adult participants; school and parental/guardian consent and child assent were obtained for all child participants.

2.2. Materials and methods

2.2.1. Adult procedure

The decision-making tasks were administered in paper-and-pencil format. The social decision-making task was administered before the objective decision-making task, and both were completed individually in a quiet testing room at the University.

2.2.1.1. Objective decision-making. For this task, only objective information was given regarding one component and a conjunction containing this component. This task was presented as a poker chip problem; the rules were set up as follows: "For this task there are two teams. Each team's aim is to randomly draw the specified color of poker chip. The rules are as follows: where the teams have two players, both players have to draw the same color to win. When all players across the two teams draw the same color, it is a draw, and the game is repeated until one team wins. Likewise, if no players draw the specified color, there are no winners, and the game is repeated until one team wins. When the games are repeated, the chips are replaced in the bags rather than removed, therefore the numbers of chips stated in each problem's description never change".

Participants then completed four separate trials in which the proportions of differently colored chips varied across the single player and two-player teams (see Table 1). As shown in Table 1, one player in the two-player team always had the same proportion of chips as the single player, with the second player in the two-player team having a proportion that varied the probability of choosing the stipulated color chip. Table 1 also shows the exact probabilities of the teams winning; following the conjunction rule, the single player team should in theory always win the game. Participants were required to give perceived probabilities using the same metrics as the social judgements (i.e., integers between 0 and 100, 0 being unlikely and 100 being likely) of the single player winning (equivalent to the probability of the component) and the two-player team winning (equivalent to the probability of the conjunction). The conjunction error was made on a trial when a higher probability of winning was given to the two-player team than to the single player team.

Table 1
Distribution of poker chips for the single and two-player teams.

Trial	Winning color	Single Player	Two-Player
Likely–Unlikely	Blue	30 red, 90 blue (0.75)	30 red, 90 blue, 30 blue, 90 red (0.19)
Unlikely–Likely	Green	30 green, 90 yellow (0.25)	30 yellow, 90 green, 30 green, 90 yellow (0.19)
Likely–Likely	Orange	30 pink, 90 orange (0.75)	30 pink, 90 orange, 30 pink 90 orange (0.56)
Unlikely–Unlikely	Brown	30 brown, 90 purple (0.25)	30 brown, 90 purple, 30 brown, 90 purple (0.06)

Note: Actual probabilities of the team winning are shown in parentheses.

2.2.1.2. Social decision-making. The Linda and Bill scenarios from Tversky and Kahneman's (1983) study were used, as well as a more recent adaption (Ollie scenario; Fisk, Marshall, Rogers, & Stock, 2023). For each vignette, participants had to rate on a scale of 0–100 the perceived probabilities of a series of statements, including statements involving a conjunction of two of the individual statements (see Supplementary Materials). The conjunction error was made on a trial when a higher probability was assigned to the conjunctive statement than one, or both of the component events.

2.2.2. Child procedure

Tasks were administered to the child participants individually in a quiet area of their school in the order described below.

2.2.2.1. Objective decision-making. This task was functionally equivalent to that administered to the adult sample and was modelled on Fisk and Slattery's (2005) procedure. Three teddy bears were split into two teams before being blindfolded: a team with two teddies and a team with just one teddy. Each teddy had their own box in front of them in which plastic building bricks were placed. The experimenter asked the child to count out the bricks as they put them in each box. The rules of the game were made clear and matched those of the poker chip problem used for adult participants. To ensure that the child understood the rules, a number of practice trials was given. The responses to the practice trials offered a chance to revisit any rules which were not understood before moving on to the test trials. Having passed the practice trials, children completed four trials in which the probabilities of the single player and two-player team were manipulated, following the procedure used with the adult participants (see Table 1). For each trial, the child was asked which team would win first. Answering team 2 constituted a conjunction fallacy, therefore a child who chose team 1 as the winner avoided the fallacy and scored 0, whereas a child who chose team 2 as the winner committed the conjunction fallacy and scored 1. Scores represent the total number of conjunction fallacies, with the maximum being 4.

2.2.2.2. Social decision-making. The social decision-making task was developed by Marshall and Meins (2024) and was designed to provide an age-appropriate method for assessing children's probability judgements about two component events and their conjunction. Children were first introduced to the scale that they would use to quantify their probability judgements. The scale consisted of a range of faces numbered 0–7 changing from a frowning sad face on the far left (0) to a smiling happy face on the far right (7). The experimenter told the child that the scale could be used to show whether people would or would not say particular things, and explained that the far left (sad face) represented things that someone definitely was not going to say (representing zero probability). Children were then shown a marker than could be stuck on the scale. The experimenter explained that the marker would go on the sad face if the child was definitely sure the person was not going to say that particular thing. The experimenter further explained that if the child was not sure, but thought the person would not say it, then the marker would stay on the 'sad' side of the scale, but would not go all the way to the left. The same explanation was then given for likely attributes in relation to the 'happy' (representing probability = 1) side of the scale. Finally, children were instructed that if they were not sure what the person would say, they should put the marker on the neutral face in the middle of the scale (representing 0.5 probability). Three practice trials tested the child's understanding of the scale, and all children passed the practice trials.

Next, children were told that a new teacher was trying to learn about the students in their class, and to do so, was drawing names out of a hat to select students to tell the class about themselves. The task was accompanied by an interactive drawing, and the experimenter demonstrated the teacher picking a name out of the hat through a slot in the picture and explained that the goal was to work out what the selected student would tell the class. There were four trials of the task (two girls and two boys), each involving two components and their conjunction. The components represented events judged likely (plays computer games, plays sports for boys; likes dancing, favorite color is pink for girls) or unlikely (wears glasses and likes vegetables for both genders) for children of this age range (Cooke & Wardle, 2005; Corcoran, 2019; Food Foundation, 2020; Homer, Hayward, Frye, & Plass, 2012; Horwood, Waylen, Herrick, Williams, & Wolke, 2005; Leonhardt & Overå, 2021; LoBue & DeLoache, 2011; Sport England, 2025; Statistica, 2025; Tuero, González-Boto, Espartero, & Zapico, 2014). As is the case in the adult version of the task, each trial had a likely–unlikely conjunction (see Supplementary Materials).

For each of the four names, the child was required to rate the probability of the likely and unlikely components and their conjunction using the scale. For example, if Jack's name was pulled out of the hat, the child had to judge the probability of him telling the class that he likes vegetables (unlikely component), plays sports (likely component), or likes vegetables and plays sports (conjunction). For each of the three probability ratings, the experimenter said, "Now think about the scale we have been using and look at the things that [Vignette name] might tell the class. Where do you think [component/conjunction] goes on the scale?" After having made the likelihood judgement, the marker was removed from the scale before the child was asked to make the next judgement. The order of presentation of the likely and unlikely components and their conjunction was randomized across the four trials. The children's judgements on the scale were converted to probabilities. The conjunction error was made on a trial when a higher probability was given to the conjunction than to one or both components. The data from the social task were published in [reference omitted for blind review]. This paper reported that the children interpreted the components as intended, assigning the likely component the highest probability, followed by the conjunction, with the unlikely component assigned the lowest probability.

3. Results

3.1. Descriptive statistics and preliminary analyses

Gender differences were investigated using MANOVA. There was no significant difference was between men and women in the adult sample across the trials of the objective decision-making task, $F(4, 77) = 0.89$, $p = .473$, $\eta^2 = 0.04$, or the social decision-making task, $F(3, 78) = 0.33$, $p = .804$, $\eta^2 = 0.01$. Likewise, no significant difference was found between boys and girls in the child sample across trials of the objective decision-making task, $F(4, 66) = 0.70$, $p = .595$, $\eta^2 = 0.04$, or the social decision-making task, $F(4, 66) = 1.32$, $p = .270$, $\eta^2 = 0.07$). Gender is therefore not considered further in the analyses reported below.

Binomial tests were used to investigate whether performance on each of the vignettes in the social decision-making task was different from chance level. Adjusting alpha for multiple comparisons ($\alpha = 0.017$), adult participants committed the conjunction fallacy significantly lower than chance for the Bill and Ollie vignettes ($ps = 0.020$, 0.005, and < 0.001, for the Linda, Bill, and Ollie vignettes respectively). The following percentage of adults made the conjunction fallacy for the Linda, Bill, and Ollie vignettes respectively: 37 %, 34 %, 22 %. Adjusting alpha for multiple comparisons ($\alpha = 0.013$), child participants committed the conjunction fallacy significantly above chance level for the Rick and Chloe vignettes ($ps = 0.017$, 0.009, 0.342, and 0.032, for the Rick, Chloe, Sally, and Jack vignettes respectively). The following percentage of children made the conjunction fallacy for the Rick, Chloe, Sally, and Jack vignettes respectively: 65 %, 66 %, 56 %, 63 %.

3.2. Conjunction fallacies on the objective decision-making task

Table 2 shows the percentage of adults making the conjunction fallacy on the different trials of the objective decision-making task. As shown in Table 2, adults were most likely to make conjunction fallacies on the trial where the single player was assigned a probability unlikely to win and one of the two-player team was assigned a probability likely to win. Binomial tests were used to investigate whether performance on each of the trials was different from chance level, with alpha adjusted for multiple comparisons ($\alpha = 0.013$). For both trials where the single player was assigned a probability likely to win, the conjunction fallacy rate was significantly lower than chance ($ps < 0.001$). The error rate was also significantly lower than chance on the trial where both the single player and two-player team were assigned probabilities unlikely to win ($p = .001$). However, errors were not significantly different from chance on the trial where the single player was assigned a probability unlikely to win and one of the two-player team was assigned a probability likely to win ($p = .097$).

Repeated measures general linear models were run to investigate changes in conjunction fallacy rate when the probabilities of the two-player team were manipulated and the single player probability was held constant. Comparing the two trials where the single player was assigned the same probability that was likely to win (see Table 1), there was no significant effect of manipulating the two-player team probabilities, $F(1, 81) = 2.03$, $p = .159$, $\eta^2 = 0.025$. Comparing the two trials where the single player was assigned the same probability that was unlikely to win, there was a significant effect of manipulating the two-player team probabilities, $F(1, 81) = 18.37$, $p < .001$, $\eta^2 = 0.227$; conjunction fallacies were more likely to occur when one of the two-player team was assigned a probability likely to win.

Table 2 also shows the percentage of children making the conjunction fallacy on the different trials of the objective decision-making task. As shown in Table 2, there was little variation in error rate across the four trials. Binomial tests indicated that children's performance was no different from chance on all four trials ($ps = 0.342$, 0.235, 0.235, and 0.154 for trials 1 to 4 respectively).

3.3. Relations between conjunction fallacies on the objective and social decision-making tasks

The pattern of findings for associations between conjunction fallacies on the two types of decision-making task was the same for parametric and non-parametric correlations; parametric correlations are reported for ease of interpretation of effect sizes. In adults, there was a positive correlation between the number of trials on which the conjunction fallacy was made on the objective and social decision-making tasks, $r(80)$

Table 2
Percentage of participants making the conjunction fallacy as a function of trial type in Study 1.

Trial	Percentage of Errors
Adults	
Likely-Unlikely	19.5 %
Unlikely-Likely	59.8 %
Likely-Likely	26.8 %
Unlikely-Unlikely	30.5 %
Children	
Likely-Unlikely	56.3 %
Unlikely-Likely	57,7 %
Likely-Likely	57.7 %
Unlikely-Unlikely	59.2 %

= 0.24, p = .030. However, in children, there was no correlation between the number of trials on which the fallacy was made on the two tasks, $r(69) = 0.02$, p = .901.

4. Discussion

The first aim of Study 1 was to investigate how manipulating the probabilities assigned to the single and two-player teams influenced the conjunction fallacy rate. Dealing first with the results from the adult participants, we replicated Fisk and Slattery's (2005) finding that the fallacy rate was higher when the single player was assigned a probability likely to win than unlikely to win when playing against a two-player team assigned a conjunction of likely and unlikely probabilities. However, the conjunction fallacy rate in Study 1 was notably higher than that reported by Fisk and Slattery: 20 % versus 9 % for the likely single player probability, and 60 % versus 29 % for the unlikely single player probability. The results of Study 1 indicate that it is not only the probability assigned to the single player that influences the conjunction fallacy rate, but the comparative probabilities of the single versus two-player teams. For example, despite the fact that the probability assigned to the single player was held constant, conjunction fallacies were significantly more likely to occur when the single player was unlikely to win and one of the two-player team was likely to win than when all three players were assigned the same (unlikely to win) probability. In contrast, there was no significant effect of manipulating the probabilities assigned to the two-player team when the single player was likely to win. These findings suggest that adults' decision-making is influenced by the likelihood of winning, regardless of which team contains the player with a high probability of winning.

Turning to children's performance on the objective decision-making task, across all four trials, 4- and 5-year-olds made the conjunction fallacy at chance level, indicating that they did not use the information provided on probability of winning to inform their judgements. In contrast, Fisk and Slattery (2005) reported that children of this age were sensitive to manipulations in the probability assigned to the single player, with a conjunction fallacy rate of 41 % when the single player was likely to win and 61 % when the single player was unlikely to win. This pattern mirrored that observed both in older children and in adults. Thus, while the results of Study 1 may indicate that 4- and 5-year-olds are not capable of probabilistic reasoning, the observed chance-level performance may be due to other factors or idiosyncrasies in the sample of children who participated in Study 1. Study 2 therefore aimed to establish whether our findings could be replicated in a separate sample of 4- and 5-year-olds.

The second aim of Study 1 was to investigate for the first time whether making conjunction fallacies on objective decision-making tasks was related to these errors when making judgements about people's social characteristics. In support of our hypothesis, there was a positive correlation between adults' errors on the two types of decision-making task, but this relation was not strong, and represented a small to medium effect size. In contrast, no such association was seen for conjunction fallacies on the two types of task in the 4- and 5-year-olds who participated in Study 1. These findings suggest that there are some common underlying processes involved in adults' probability-based decision-making across these varied types of judgement, but that these two types of decision-making may rely on distinct mechanisms in early childhood. Study 2 sought to replicate the null finding for 4- to 5-year-olds' conjunction fallacies on the objective and social tasks and also included a wider age range of children to attempt to establish the age at which these errors become positively associated, and thus identify the point in development where objective and social probability judgements may begin to depend on the same underlying cognitive processes.

It is worthwhile to note that, while we observed higher conjunction fallacy rates in adults' performance on the objective decision-making task compared with those reported by Fisk and Slattery (2005), adults' fallacy rates on the social decision-making task in Study 1 were notably lower than those reported in the extant literature. For example, Tversky and Kahneman (1983) reported conjunction fallacy rates of 87 % for the Bill scenario and 85 % for the Linda scenario. Using the same rating procedure as Study 1, with participants rating the likelihood between 0 and 100 of the conjunction and its components, 70 % assigned a higher probability to the conjunction than to either or both of its component statements (Tversky & Koehler, 1994). In contrast, adults' conjunction fallacy rates varied between 22 % and 37 % in Study 1. Given these discrepancies with previous research, Study 2 sought to establish if Study 1's findings could be replicated in a separate sample of adults.

Study 2 also included an adaptation of the social decision-making task to investigate in greater detail relations between conjunction fallacies when making objective versus social judgements. Marshall and Meins (2024) investigated whether adults and children make conjunction fallacies on social decision-making tasks in the absence of being given any background information on the vignette characters. This version of the task is arguably a 'purer' assessment of individuals' understanding of the rules of probability given that there is no background information to bias the likelihood of a particular characteristic. Avoiding the conjunction fallacy on the social task when there is no background information may therefore be equivalent to understanding the conjunction rule. One might therefore predict that performance on this version of the social decision-making task would be more strongly positively correlated with performance on the objective decision-making task compared with the standard version of the task, in which background information is provided. Study 2 tested this hypothesis.

In summary, Study 2 aimed to (a) replicate the findings of Study 1 with regard to how manipulating individual probabilities in the objective task influenced the conjunction fallacy rate in adults and children, (b) replicate the pattern of association between conjunction fallacies on objective and social decision-making tasks in adults and children, and (c) explore conjunction fallacy rates on the different types of task across development. We predicted that children's performance on the decision-making tasks would become more similar to that of adults as children got older. Study 2 also investigated how social conjunction fallacies in the absence of background information related to adults' and children's errors on an objective decision-making task, predicting a positive correlation in performance on the two tasks.

5. Study 2

5.1. Participants

Adult participants were 130 psychology undergraduate students (108 women, 22 men; 104 White, 14 Asian, two Black; mean age 19.8 years, $SD = 1.83$, range 18–27) who volunteered via the University's online participant recruitment website; participants were rewarded with course credit. The adult sample was appropriately powered to detect small to medium effects for the binomial and correlational analyses (power > 0.94). The youngest age group of child participants ($n = 69$; 31 girls, 38 boys; 58 White, nine Asian, two Black) was recruited from two schools in North-West England; mean age 58.6 months, $SD = 2.97$, range 53–65 months. The middle age group of children ($n = 46$; 22 girls, 24 boys; 40 White, six Asian) was recruited from one school in North-East and one in North-West England; mean age 102.2 months, $SD = 8.70$, range 90–119 months. The eldest group of children ($n = 33$; 19 girls, 14 boys; 29 White, four Asian) was recruited from two schools in North-West England; mean age 129.4 months, $SD = 4.40$, range 120–135 months. Teachers reported that none of the children had any diagnosed learning or neurological disorder. Children were rewarded for their participation with stickers. Note that testing had to be abandoned early because of the COVID-19 pandemic, resulting in the two older groups being smaller than the youngest group. The child samples were appropriately powered to detect medium size effects for the binomial analyses (power > 0.94), but the smallest child samples were underpowered to detect medium size correlations; Bayesian analyses were therefore used to confirm the results.

The study was approved by the relevant University Ethics Committee, and data were gathered in accordance with the ethical code of practice of the British Psychological Society and fully complied with the Data Protection Act 1998. Fully informed written consent was obtained for adult participants; school and parental/guardian consent and child assent were obtained for child participants.

5.2. Materials and methods

Adult participants completed tasks individually in a testing room at the University, and the experimenter administered the tasks to the child participants in a quiet area of their school. All tasks were administered in computerized format in the order described below.

5.2.1. Adult procedure

5.2.1.1. Objective decision-making. The task used to assess objective decision-making was identical to that used in Study 1.

5.2.1.2. Social decision-making. The task and procedure were identical to Study 1 apart from the following changes. First, participants completed a fourth vignette (Ashleigh) in addition to the Linda, Bill, and Ollie vignettes used in Study 1 (see Supplementary Materials). Second, participants gave a baseline judgement on the probability of each component and the conjunction in the absence of any information on the vignette character, other than their name. Participants were then provided with background information about the vignettes' characters, after which they made the same probability judgements for a second time. Note that participants were not able to access their pre-information judgements when judging the probabilities for a second time. The rate of conjunction errors was scored separately for the pre- and post-information conditions.

5.2.2. Child procedure

5.2.2.1. Objective decision-making. The task used to assess objective decision-making was identical to that used in Study 1.

5.2.2.2. Social decision-making. The task and procedure were identical to those administered in Study 1, but children were first asked to rate the likelihood of the two components and their conjunction for each of the four characters before being presented with any background information, other than their name. Having made these judgements, the experimenter told the child a short story, accompanied by a laptop-presented storyboard that illustrated a day in the life of the particular character which reinforced the likelihood of one of the component characteristics (see Supplementary Materials). For example, to reinforce the likelihood of Jack liking sports, the narrative and storyboard detailed how he enjoyed time in the playground at school more than his lessons, that he had scored two goals that day in his PE lesson, and was keen to tell his parents how well he had done. The child was then asked to judge the two components and the conjunction using the scale described in Study 1, before moving on to the next character's story. Conjunction fallacy rate was scored separately for the pre- and post-information conditions using the same scoring system as described in Study 1.

6. Results

6.1. Descriptive statistics and preliminary analyses

Gender differences were investigated using MANOVA. There was no significant difference between men and women in the adult sample across trials of the objective decision-making task, $F(4, 125) = 1.10$, $p = .361$, $\eta^2 = 0.03$, the pre-information social decision-making task, $F(4, 125) = 0.52$, $p = .723$, $\eta^2 = 0.02$), or the post-information social decision making task, $F(4, 125) = 1.05$, $p = .378$, $\eta^2 = 0.03$. Likewise, no significant difference was found between boys and girls in the child sample across trials of the objective decision-making task, $F(4, 143) = 0.98$, $p = .418$, $\eta^2 = 0.03$, the pre-information social decision-making task, $F(4, 143) = 1.10$, $p = .358$, $\eta^2 = 0.03$, or the post-information social decision-making task, $F(4, 143) = 2.35$, $p = .057$, $\eta^2 = 0.06$. Gender is therefore not considered further in the analyses reported below.

Binomial tests were used to investigate whether performance on each of the vignettes in the social decision-making task was different from chance level, with alpha adjusted for multiple comparisons ($\alpha = 0.013$) for both adult and child participants. In the pre-information condition, adult participants committed the conjunction fallacy significantly lower than chance for all vignettes (*p*s < 0.001). The following percentage of adults made the conjunction fallacy for the Linda, Bill, Ollie, and Ashleigh vignettes respectively: 19 %, 19 %, 13 %, 21 %. In the post-information condition, adult participants committed the conjunction fallacy no differently from chance for all vignettes (*p*s 0.254, 0.028, 0.136, and 0.930 for the Linda, Bill, Ollie, and Ashleigh vignettes respectively). The following percentage of adults made the conjunction fallacy for the Linda, Bill, Ollie, and Ashleigh vignettes respectively: 45 %, 40 %, 43 %, 49 %.

In the pre-information condition, the 4- and 5-year-olds' performance did not differ from chance on any of the four vignettes (*p*s = 0.336, 0.228, 0.630, and 0.810, for the Rick, Chloe, Sally, and Jack vignettes respectively). The following percentage of 4- and 5-year-olds made the conjunction fallacy for the Rick, Chloe, Sally, and Jack vignettes respectively: 43 %, 42 %, 46 %, 48 %. In the post-information condition, the 4- to 5-year-olds' performance did not differ from chance on any of the four vignettes (*p*s = 0.630, 0.148, 1.00, and 0.470, for the Rick, Chloe, Sally, and Jack vignettes respectively). The following percentage of 4- and 5-year-olds made the conjunction fallacy for the Rick, Chloe, Sally, and Jack vignettes respectively: 46 %, 41 %, 51 %, 45 %.

In the pre-information condition, 7- to 9-year-olds made the conjunction fallacy significantly above chance for the Rick and Jack vignettes (*p*s < 0.001, 0.302, 0.011, < 0.001 for the Rick, Chloe, Sally, and Jack vignettes respectively). The following percentage of 7- to 9-year-olds made the conjunction fallacy for the Rick, Chloe, Sally, and Jack vignettes respectively: 83 %, 59 %, 70 %, 80 %. In the post-information condition, the conjunction fallacy was made significantly above chance for all of the four vignettes (*p*s < 0.001 for Rick, Chloe, Sally, $p = .002$ for Jack). The following percentage of 7- to 9-year-olds made the conjunction fallacy for the Rick, Chloe, Sally, and Jack vignettes respectively: 78 %, 85 %, 89 %, 74 %.

In the pre-information condition, 10- to 11-year-olds' performance did not differ from chance on any of the four vignettes (*p*s = 0.080, 0.487, 0.163, and 0.296, for the Rick, Chloe, Sally, and Jack vignettes respectively). The following percentage of 10- to 11-year-olds made the conjunction fallacy for the Rick, Chloe, Sally, and Jack vignettes, respectively: 67 %, 58 %, 64 %, 61 %. In the post-information condition, 10- to 11-year-olds made the conjunction fallacy significantly above chance for all vignettes (*p*s < 0.001 for Chloe, Sally, and Jack, $p = .005$ for Rick). The following percentage of 10- to 11-year-olds made the conjunction fallacy for the Rick, Chloe, Sally, and Jack vignettes, respectively: 76 %, 94 %, 79 %, 91 %.

6.2. Conjunction fallacy rate on the objective decision-making task

Table 3 shows the percentage of adults making the conjunction fallacy on the different trials of the objective decision-making task. Replicating the findings of Study 1, adults were most likely to make conjunction fallacies on the trial where the single player was assigned a probability unlikely to win and one of the two-player team was assigned

Table 3
Percentage of participants making the conjunction fallacy as a function of trial type in Study 2.

Trial	Percentage of Errors
Adults	
Likely-Unlikely	30.8 %
Unlikely-Likely	55.4 %
Likely-Likely	41.5 %
Unlikely-Unlikely	43.1 %
4- and 5- year olds	
Likely-Unlikely	44.9 %
Unlikely-Likely	58.0 %
Likely-Likely	49.3 %
Unlikely-Unlikely	58.0 %
7- to 9- year olds	
Likely-Unlikely	54.3 %
Unlikely-Likely	60.9 %
Likely-Likely	52.2 %
Unlikely-Unlikely	50.0 %
10- and 11- year olds	
Likely-Unlikely	36.4 %
Unlikely-Likely	54.5 %
Likely-Likely	45.5 %
Unlikely-Unlikely	45.5 %

a probability likely to win; a binomial test showed that the conjunction fallacy rate was not significantly different from chance ($p = .254$). The conjunction fallacy rate was significantly below chance ($p < .001$) for the trial where the single player was assigned a probability likely to win and one player in the two-player team was assigned a probability unlikely to win. For the trial where the single player was assigned a probability likely to win and both players in the two-player team were also assigned likely probabilities, the conjunction fallacy rate was non-significantly lower than chance ($p = .065$). For the trial where all three players were assigned a probability unlikely to win, the error rate was no different from chance ($p = .136$).

Repeated measures general linear models were run to investigate changes in conjunction fallacy rate when the probabilities of the two-player team were manipulated and the single player probability was held constant. Comparing the two trials where the single player was assigned the same probability that was likely to win, there was a significant effect of manipulating the two-player team probabilities, $F(1, 129) = 6.38$, $p = .013$, $\eta^2 = 0.049$; conjunction fallacies were more likely to occur when both members of the two-player team were assigned a probability likely to win. Replicating the findings of Study 1, comparing the two trials where the single player was assigned the same probability that was unlikely to win, there was a significant effect of manipulating the two-player team probabilities, $F(1, 129) = 5.29$, $p = .023$, $\eta^2 = 0.041$; conjunction fallacies were more likely to occur when one of the two-player team was assigned a probability likely to win.

Table 3 also shows the percentage of children in the three age groups making the conjunction fallacy on the different trials of the objective decision-making task. Binomial tests indicated that children's conjunction errors were no different from chance on all four trials for the 4- and 5-year-olds (*ps* = 0.470, 0.228, 1.00, and 0.228 for trials 1 to 4 respectively), 7- to 9-year-olds (*ps* = 0.470, 0.228, 1.00, and 0.228 for trials 1 to 4 respectively), and 10- and 11-year-olds (*ps* = 0.163, 0.728, 0.728, and 0.728 for trials 1 to 4 respectively).

6.3. Relations between conjunction fallacies on the objective and social decision-making tasks

The pattern of findings for associations between fallacies on the two types of decision-making task was the same for parametric and non-parametric correlations; parametric correlations are reported for ease of interpretation of effect sizes. Replicating the findings of Study 1, adults' conjunction fallacies on the objective decision-making task were positively correlated with errors on the standard (post-information) version of the social decision-making task, $r(128) = 0.22$, $p = .014$, but fallacies on the objective task were non-significantly correlated with those on the pre-information version of the social task, $r(128) = 0.15$, $p = .083$. Study 2 also replicated Study 1's findings in relation to 4- and 5-year-olds' task performance, with no association between conjunction fallacies on the objective task and the standard (post-information) version of the social decision-making task $r(67) = 0.01$, $p = .929$; fallacies were also unrelated on the pre-information version of the task, $r(67) = 0.11$, $p = .263$. These relations were further investigated using Bayesian analyses, with the Bayes factor set to BF_{01} to indicate the strength of evidence in favor of the null hypothesis. The Bayesian analyses indicated strong (Bayes factor 10.52) or substantial (Bayes factor 6.98) support for the null hypotheses for these two correlations respectively. There was no association between fallacies on the two types of task in the 7- to 9-year-olds: $r(44) = 0.14$, $p = .366$ for the standard version; $r(44) = 0.05$, $p = .730$, for the pre-information version of the social decision-making task. Bayesian analyses indicated substantial support for the null hypothesis for both correlations (Bayes factor 5.79 and 8.18, respectively). In 10- to 11-year-olds, conjunction fallacies on the objective task were positively correlated with fallacies on the standard version of the social task, $r(31) = 0.45$, $p = .009$, but were non-significantly correlated with fallacies on the pre-information version of the task, $r(31) = 0.21$, $p = .249$. Bayesian analyses indicated substantial support for the positive association between fallacies on the objective task and the standard version of the social task (Bayes factor 0.24), but substantial support for the null hypothesis for the association between fallacies on the objective task and the pre-information version of the social task (Bayes factor 3.83).

7. Discussion

Study 2 aimed to replicate and extend the findings of Study 1 in relation to conjunction fallacies on the objective decision-making task and their association with these errors when making judgements about people's social characteristics. Study 2 replicated the finding that conjunction fallacies were most likely to be made by adults on the objective decision-making trial when the single player was assigned a probability unlikely to win and one of the two-player team was assigned a probability likely to win. We also replicated the finding that, on the two trials where the single player was assigned the same probability that was unlikely to win, manipulating the two-player team probabilities had a significant effect on error rate, with conjunction fallacies being more likely to occur when one of the two-player team was assigned a probability likely to win.

In Study 2, there was also a significant effect of manipulating the two-player team probabilities on the trials where the single player was likely to win; conjunction fallacies were more likely to occur when both members of the two-player team were assigned a probability likely to win. In Study 1, this effect was in the same direction, but was non-significant. The results of Studies 1 and 2 therefore indicate that conjunction fallacies arise because of adults making comparative judgements based on the probabilities assigned to both teams, and highlight how their decision-making appears to be particularly biased in favor of probabilities that are likely, rather than unlikely, to win. With regard to the 4- and 5-year-olds, Study 2 replicated the chance level of conjunction fallacies observed in Study 1 on the objective decision-making task. Study 2 also explored conjunction fallacies across development. Like the 4- and 5-year-olds, both groups of older children made conjunction fallacies at chance level on all four trials of the objective decision-making task. These findings suggest that across the first decade of life, children have difficulty in judging objective probabilities and, unlike adults, are not influenced by the comparative probabilities assigned to different teams or biased in favor of probabilities likely to win.

The association between conjunction fallacies on the objective and social tasks did, however, differ across development. We replicated

Study 1's findings of (a) a positive association between fallacies on the objective and standard version of the social decision-making task in adults, and (b) no association in fallacies on the two types of task in 4- and 5-year-olds. We also found that fallacies on the two types of task were unrelated in 7- to 9-year-olds, but the performance of the 10- and 11-year-olds' mirrored that of adults, with a significant positive correlation between conjunction fallacies on the objective task and the standard version of the social decision-making task. Conjunction fallacies when making these different types of judgement may thus begin to rely on common underlying mechanisms by the end of the first decade of life.

The final aim of Study 2 was to investigate whether conjunction fallacies in judging social characteristics in the absence of background information related to adults' and children's fallacies on the objective decision-making task. We suggested that such fallacies about social judgements might be more strongly related to fallacies on the objective task because they may index the ability to understand the conjunction rule and thus be more similar to objective probability judgements compared with social judgements made in the context of background information. The results of Study 2 found no support for this argument. In both adults and 10- to 11-year-olds, conjunction fallacies on the objective task were significantly correlated with those on the standard version of the social decision-making task, but not with those on the pre-information version of this task. These findings further suggest that, while there may be some common underlying decision-making processes in making judgements about objective probabilities and people's social characteristics in older children and adults, the strength of the association between these two types of judgement is at best modest. Establishing the mechanisms that are unique to objective versus social probability judgements is therefore an important task. We return to this issue in the General Discussion.

8. Study 3

The aim of Study 3 was to investigate potential cognitive processes related to adults' tendency to make conjunction fallacies on objective and social decision-making tasks. As discussed in the Introduction, dual process theories of cognition (Kahneman, 2002, 2011) distinguish between Type 1 and Type 2 thinking, with Type 1 thinking being the default mode for quick decision-making. However, with experimenter manipulation, it may be possible to slow a participant's approach to answering questions, potentially shifting their cognitive processing from Type 1 to Type 2 (Bago & De Neys, 2017). For example, during "thinking aloud" procedures, participants typically perform a task while openly describing their concurrent thought processes (Ericsson & Simon, 1980). Thinking aloud has a slowing effect on cognition (Fox & Charness, 2010; Jääskeläinen, 2010), which may result in a reliance on Type 2 rather than Type 1 processes.

The aim of Study 3 was to employ a thinking aloud paradigm in order to explore whether Type 1 processes play a role in producing conjunction fallacies in adults. The Type 1 thinking proposed to determine the conjunction fallacy is the reliance on the representativeness heuristic in making judgements about objective probabilities (Fisk & Slattery, 2005) or social characteristics (Tversky & Kahneman, 1983). If this proposal is correct, performance should be better in the thinking aloud versus silent procedure. Thinking aloud could reasonably be assumed to be useful in making both objective and social judgements, but Type 1 heuristic-based thinking might be particularly common when judging people's characteristics based on background knowledge and context, and so attempting to shift thinking to Type 2 processes may be especially useful for avoiding decision-making errors on social tasks. Study 3 therefore explored whether the thinking aloud procedure was effective in reducing conjunction fallacies on both objective and social decision-making tasks. We also expected to replicate the findings of Studies 1 and 2 with regard to (a) the influence of manipulating the assigned probabilities on the rate of conjunction fallacies in the objective decision-making task, and (b) the positive association between conjunction fallacies observed on the objective and social decision-making tasks.

9. Method

9.1. Participants

Participants were 76 psychology undergraduate students (66 women, 10 men; 60 White, 10 Asian, six Black; mean age 19.7 years, *SD* = 1.51, range 18–27) who volunteered via the University's online participant recruitment website; participants were rewarded with course credit. The study was appropriately powered to detect medium size effects for the binomial, correlational, and paired-samples *t*-test analyses (power > 0.85). The study was approved by the relevant University Ethics Committee, and data were gathered in accordance with the ethical code of practice of the British Psychological Society and fully complied with the Data Protection Act 1998. Fully informed written consent was obtained.

9.2. Materials and methods

9.2.1. Decision-making tasks

Both the objective and social decision-making tasks were administered on a laptop and were split between a thinking aloud procedure and a silent (standard) procedure, with all participants completing both thinking aloud and silent conditions. Participants completed the objective task first, followed by the social decision-making task in the silent condition, then both tasks were repeated in the thinking aloud condition.

The silent version of the objective decision-making task was identical to that used in Studies 1 and 2. In Study 3, participants completed four additional trials in the thinking aloud condition. The conjunction error was made on a trial when a higher probability of winning was given to the two-player team than to the single player team.

The silent version of the social conjunction task was identical to that in Study 1 and used the same three vignettes (Linda, Bill, and Ollie). Participants completed a further three vignettes in the thinking aloud condition (see Supplementary Materials). The conjunction error was made on a trial when a higher probability was given to the conjunction than to one or both of the components.

The thinking aloud instructions, based on guidance from Van Someren, Barnard, and Sandberg (1994), were as follows: "In this experiment we're trying to find out how people solve everyday reasoning problems. Therefore, I'm going to ask you to 'think aloud' when you're solving the problems. Start by reading the complete problem aloud. Then when you're solving the problem, you should say out loud everything that you're thinking about. Any thought, I want you to say it, all comments you're thinking of, anything that helps you understand the problem or come to your answer, any thought, any feeling, basically everything that is going through your mind, please say aloud. You should be talking almost continuously until you give your final answer. Try to keep thinking aloud the whole time. Whenever you're not saying anything for a while, I'll remind you to speak aloud."

10. Results

10.1. Descriptive statistics and preliminary analyses

Gender differences were investigated using MANOVA. No significant difference was found between men and women across trials of the silent objective decision-making task, $F(4, 71) = 0.76$, $p = .556$, $\eta^2 = 0.04$, the thinking aloud objective decision-making task, $F(4, 71) = 0.58$, $p = .676$, $\eta^2 = 0.03$, the silent social decision-making task, $F(3, 72) = 0.69$, $p = .562$, $\eta^2 = 0.03$, or the thinking aloud social decision-making task, $F(3, 72) = 0.84$, $p = .478$, $\eta^2 = 0.03$. Gender is therefore not considered further in the analyses reported below.

Binomial tests were used to investigate whether performance on each of the vignettes in the silent condition of the social decision-making task was different from chance level, adjusting alpha for multiple comparisons ($\alpha = 0.017$). Adult participants committed the conjunction fallacy significantly above chance for all vignettes (*ps* 0.004, < 0.001, and 0.002 for the Linda, Bill, and Ollie vignettes respectively). The following percentage of adults made the conjunction fallacy for the Linda, Bill, and Ollie vignettes respectively: 67 %, 74 %, 68 %.

In the thinking aloud condition, binomial tests indicated that the conjunction fallacy was committed significantly above chance for the tennis and Ashleigh vignettes (*ps* 0.015 and 0.002 respectively), but errors were not above chance level for the Lisa vignette, $p = .909$. The following percentage of adults made the conjunction fallacy for the tennis, Ashleigh, and Lisa vignettes respectively: 65 %, 68 %, 49 %.

10.2. Conjunction fallacy rate on the objective decision-making task

Table 4 shows the shows the percentage of adults making the conjunction fallacy on the different trials of the silent version of the objective decision-making task. Alpha was adjusted for multiple comparisons ($\alpha = 0.013$). Replicating the findings of Studies 1 and 2, adults were most likely to make conjunction fallacies on the trial where the single player was assigned a probability unlikely to win and one of the two-player team was assigned a probability likely to win, and a binomial test showed that the conjunction fallacy rate was significantly above chance ($p < .001$). For the trial where the single player was assigned a probability likely to win, and one of the two-player team was assigned a probability unlikely to win, the conjunction fallacy rate was significantly below chance ($p < .001$). For the trial where all three players were assigned a probability likely to win or unlikely to win, the conjunction fallacy rate was no different from chance (*ps* = 0.207, 0.302, respectively).

Repeated measures general linear models were run to investigate changes in conjunction fallacy rate when the probabilities of the two-player team were manipulated and the single player probability was held constant. Replicating the findings of Study 2, comparing the two trials where the single player was assigned the same probability that was likely to win, there was a significant effect of manipulating the two-player team probabilities, $F(1, 75) = 4.00$, $p = .049$, $\eta^2 = 0.053$; conjunction fallacies were more likely to occur when both members of the two-player team were assigned a probability likely to win. Replicating the findings of Studies 1 and 2, comparing the two trials where the single player was assigned the same probability that was unlikely to win, there was a significant effect of manipulating the two-player team probabilities, $F(1, 75) = 15.10$, $p < .001$, $\eta^2 = 0.201$; conjunction fallacies were more likely to occur when one of the two-player team was assigned a probability likely to win.

Table 4 also shows the shows the percentage of adults making the conjunction fallacy on the different trials of the thinking aloud version of the objective decision-making task. As shown in Table 4, adults were most likely to make conjunction fallacies on the trial where the single player was assigned a probability unlikely to win and one of the two-player team was assigned a probability likely to win, and a binomial test showed that the conjunction fallacy rate was significantly above chance ($p = .029$). For the trial where the single player was assigned a probability likely to win, and one of the two-player team was assigned a probability unlikely to win, the conjunction fallacy rate was significantly below chance ($p = .001$). For the trial where all three players were assigned a probability likely to win, the conjunction fallacy rate was no different from chance ($p = .302$). For the trial where all three players were assigned a probability unlikely to win, the conjunction fallacy rate was significantly lower than chance ($p = .015$).

Table 4
Percentage of participants making the conjunction fallacy as a function of trial type in silent and thinking aloud conditions of the objective decision-making task.

	Percentage of Errors	
Trial	Silent	Thinking Aloud
Likely-Unlikely	27.6 %	30.3 %
Unlikely-Likely	72.4 %	63.2 %
Likely-Likely	42.1 %	43.4 %
Unlikely-Unlikely	43.4 %	35.5 %

Repeated measures general linear models were run to investigate changes in conjunction fallacy rate when the probabilities of the two-player team were manipulated and the single player probability was held constant. Comparing the two trials where the single player was assigned the same probability that was likely to win, there was no significant effect of manipulating the two-player team probabilities, $F(1, 75) = 1.00$, $p = .321$, $\eta^2 = 0.013$. Comparing the two trials where the single player was assigned the same probability that was unlikely to win, there was a significant effect of manipulating the two-player team probabilities, $F(1, 75) = 7.92$, $p = .006$, $\eta^2 = 0.106$; conjunction fallacies were more likely to occur when one of the two-player team was assigned a probability likely to win.

10.3. Does thinking aloud reduce adults' conjunction fallacies?

For the objective decision-making task, the mean number of conjunction fallacies on the silent and thinking aloud conditions was as follows: silent $M = 1.87$, $SD = 1.17$; thinking aloud $M = 1.72$, $SD = 1.32$. A paired samples *t*-test showed that there was no significant difference in fallacy rate on the silent and thinking aloud conditions, $t(75) = 0.99$, $p = .325$, $d = 0.11$.

For the social decision-making task, the mean number of conjunction fallacies on the silent and thinking aloud conditions was as follows: silent $M = 2.11$, $SD = 1.15$; thinking aloud $M = 1.82$, $SD = 0.96$. A paired samples *t*-test showed that the error rate was lower on the thinking aloud condition compared with the silent condition, $t(75) = 2.17$, $p = .033$, $d = 0.25$.

10.4. Relations between conjunction fallacies on the objective and social decision-making tasks

The pattern of findings for associations between errors on the two types of decision-making task was the same for parametric and non-parametric correlations; parametric correlations are reported for ease of interpretation of effect sizes. There was positive, non-significant correlation between the number of trials on which the error was made on the silent conditions of the objective and social decision-making tasks, $r(74) = 0.19$, $p = .102$, but errors on the thinking aloud conditions of the tasks were unrelated, $r(74) = -0.02$, $p = .867$.

11. General Discussion

The overarching aim of the three studies reported here was to evaluate Tversky and Kahneman's (1983) proposal that conjunction fallacies arise due to a reliance on the representativeness heuristic. We first addressed this question by investigating how the probabilities assigned to the individual players in objective decision-making tasks relate to the rate of conjunction fallacies in both adults and children. If the conjunction fallacy is governed by the representativeness heuristic, the probability that is likely to win (i.e., representative) should influence proneness to the conjunction fallacy, regardless of which player is assigned this likely probability. Previous research had shown that adults were more likely to make conjunction fallacies when the single player was assigned a probability that was unlikely rather than likely to win (Fisk & Slattery, 2005). This finding was replicated in all three of our studies, but our results showed for the first time that conjunction fallacies were also influenced by the probabilities assigned to the two-player team. Studies 1, 2, and 3 supported our hypothesis that errors would be most common when the single player was assigned a probability unlikely to win and one of the two-player team was assigned a probability likely to win. Moreover, in all three studies, conjunction fallacies on this trial were significantly more likely to occur compared with the trial where all three players had the same probability that was unlikely to win. We also found a significant effect of manipulating the two-player team probabilities on the trials where the single player was likely to win. In Studies 2 and 3, conjunction fallacies were significantly more likely to occur when both members of the two-player team were assigned a probability likely to win. In Study 1, this effect was in the same direction, but was non-significant. The results of all three studies therefore indicate that conjunction fallacies arise due to adults making comparative judgements based on the probabilities assigned to both teams, and highlight how their decision-making appears to be particularly biased in favor of probabilities that are likely, rather than unlikely, to win. These findings are thus in line with the proposal that the representativeness heuristic is responsible for adults' conjunction fallacies on this task.

In contrast to these results across the three studies for adults, we found no evidence that children's performance on the objective decision-making task was influenced by manipulating the probabilities assigned either to the single player or two-player team. Making conjunction fallacies was no different from chance for all trials of the task and for all age groups assessed, suggesting that children up to age 11 do not undertake an odds-based, comparative probabilistic judgement process in making these decisions. Reliance on the representativeness heuristic therefore does not appear to explain children's proneness to the conjunction fallacy in making objective probability judgements.

The second way in which we investigated the role of the representativeness heuristic in conjunction fallacies was by exploring how conjunction fallacies on objective decision-making tasks relate to these fallacies on social decision-making tasks. Due to the fact that conjunction fallacy rates have been found to be considerably higher when judging the likelihood of social characteristics versus objective probabilities (e.g., Fisk & Slattery, 2005; Tversky & Kahneman, 1983), we predicted that adults' errors on the two types of task would be positively correlated, but expected the size of this relation to be modest. The results supported this prediction, with positive correlations representing small to medium effect sizes (*r*s 0.19 to 0.24) across the three studies. These findings suggest that there are some common cognitive processes—such as reliance on the representativeness heuristic—involved in adults' decision-making in judging objective probabilities and social characteristics. Study 2 investigated whether the association between objective and social decision-making errors would be stronger if participants judged the likelihood of social characteristics in the absence of any background information. This adaptation of the social decision-making task did not influence the magnitude of the relation between conjunction fallacies on the two types of task, and the correlation remained a small to medium effect size ($r = 0.15$).

Although performance on the objective decision-making task did not differ across development, there was an age-related change in the relation between conjunction fallacies on the objective and social decision-making tasks. While there was no relation in errors on the two types of task for 4- and 5-year-olds and 7- to 9-year-olds, 10- and 11-year-olds showed the same pattern observed in adults, with a positive correlation between conjunction errors on the objective and social decision-making tasks. These findings show that, as they get older, children begin to make decisions across these two tasks in ways similar to adults. Moreover, they suggest that, by the end of the first decade of life, children may begin to rely on the representativeness heuristic in making these decisions.

Finally, Study 3 addressed the role of the representativeness heuristic in adults' proneness to the conjunction fallacy by using a thinking aloud paradigm to attempt to help adults avoid Type 1 heuristic-based thinking. Adults performed the objective and social decision-making tasks under a standard, silent condition, and a condition in which they voiced their continuous thought processes out loud. The thinking aloud process resulted in a significant decrease in the number of conjunction fallacies on the social task, but not the objective task. In the thinking aloud condition, errors on the two types of task were no longer positively correlated. These findings are in line with the proposal that the representativeness heuristic is responsible for conjunction fallacies when making decisions about social characteristics. However, these findings suggest that heuristic-based thinking may not determine these errors when making objective probabilistic judgements. Thus, the results across our three studies are not entirely consistent with the proposal that conjunction fallacies on objective tasks result from reliance on the representativeness heuristic. Future research is therefore needed to establish the role of Type 1 versus Type 2 thinking in conjunction fallacies on tasks where participants are provided with objective information from which actual probabilities can be calculated.

The results across our three studies highlight some commonalities in decision-making errors when judging objective probabilities and social characteristics, and suggest that children's judgements begin to show the same errors that are seen in adults' judgements by the end of the first decade of life. However, our findings shed little light on the cognitive processes that are common to objective and social judgements or those that are specific to making errors about objective probabilities versus the likelihood of an individual having certain social characteristics. The fact that children's errors on the objective decision-making task did not differ across the first decade of life suggests that development of core cognitive abilities such as language, reasoning, and mathematical cognition—all of which show dramatic improvement between 4 and 11 years of age—are unlikely to determine children's proneness to the conjunction fallacy. Formal tutoring in probability may therefore be necessary to avoid making errors on the objective decision-making task. Future research could explore this possibility. It seems intuitive that experience of encountering different people and stereotypes associated with certain types of individual will be more likely to play a role in the conjunction fallacy when making social judgements than when judging objective probabilities. Aspects of social understanding may therefore be distinct to errors on social judgement tasks. That said, prejudice and hindsight bias were found to be unrelated to both adults' and children's proneness to the conjunction fallacy on social tasks, and children's error rate was also unrelated to their theory of mind performance (Marshall & Meins, 2024). Identifying other facets of social understanding that are correlates of conjunction fallacies on social tasks is therefore a fruitful avenue for future research.

Aside from the question of whether our findings support the proposal that the representativeness heuristic underlies the conjunction fallacy, a number of findings across the three studies are worthy of discussion. In Study 1, adults' errors on the different trials of the objective decision-making task varied between 20 % and 60 %, in Study 2 errors varied between 31 % and 55 %, and in Study 3, errors in the standard version of the task varied between 29 % and 72 %. In each study, participants were psychology undergraduates from the same university, so there is no obvious explanation for this variation. Comparing our data with those reported in Fisk and Slattery's (2005) original study, they reported that 9 % of participants made the fallacy error on the trial where the single player was assigned a probability likely to win, whereas between 20 % and 31 % of participants made the error across the studies reported here. For the trial where the single player was assigned a probability unlikely to win, Fisk and Slattery reported an error rate of 29 %, compared with rates ranging from 55 % to 72 % in our studies. Like our participants, those in Fisk and Slattery's (2005) study were psychology undergraduates, so once again, it is difficult to establish why such variation in errors was observed. These findings highlight how variable and common these decision-making errors are even in highly educated and numerate individuals. Future research should therefore explore whether conjunction fallacies on objective tasks are systematically related to individual differences in other aspects of cognition.

Error rates on the social decision-making task also varied widely across the three studies and in comparison with previous research. In Study 1, adults' error rates varied between 22 % and 34 %, in Study 2, the error rate was between 40 % and 49 %, but in Study 3, the rate varied between 67 % and 74 %. In the procedure we employed in all three studies, participants were asked to rate the likelihood between 0 and 100 of the conjunction and its components, with participants making the conjunction fallacy if they assigned a higher probability to the conjunction than to either or both of its component statements. Using this same procedure, Tversky and Koehler (1994) reported that 70 % of participants made the conjunction fallacy. Thus, while the error rate in Study 3 is in line with these previous findings, the error rates in Studies 1 and 2 are substantially lower. As was the case for the objective decision-making task, it is difficult to establish why the error rates varied across our three studies. But despite the variation in both types of error across the three studies, the pattern of findings remained constant, with (a) adults showing a bias for likely probabilities in the objective decision-making task, and (b) modest positive correlations between conjunction fallacies on the objective and social decision-making tasks. These findings are thus replicable and can be considered to be robust.

The results of the three studies reported here should be considered in light of certain limitations. The three samples of adult participants consisted exclusively of psychology undergraduates and were therefore somewhat homogeneous. The adult and child samples were also predominantly White. Future research involving more diverse groups of adults and children is therefore required to establish whether our findings generalize to other populations. The numbers of participants in some of the samples of children were also somewhat low, due to testing having to be abandoned due to the COVID-19 pandemic. That said, the smallest sample of children (the 33 10- to 11-year-olds in Study 2) was the only group to yield a statistically significant effect for the relation between conjunction fallacies on the objective and social decision-making tasks. In the other age groups in Studies 1 and 2, correlations for this relation ranged between 0.01 and 0.14, representing trivial to small effect sizes. Taken together, these findings do not suggest that lack of statistical power can explain the pattern of findings observed in the child participants.

In summary, the results of the three studies reported here highlight a bias toward probabilities likely to win in adults' decision-making about objective probabilities. In contrast, across the first decade of life, children do not appear to be sensitive to variations in probability when making objective judgements, and perform at chance level on objective decision-making tasks. By taking a developmental approach, we were able to establish that by the end of the first decade of life, children's judgements about people's social characteristics are more prone to the errors observed in adults. The positive association between conjunction fallacies on objective and social tasks observed exclusively in older children and adults indicates that judgements about these characteristics may rely to some extent on common cognitive processes by age 10.

CRediT authorship contribution statement

Dean A. Marshall: Writing – original draft, Project administration, Funding acquisition, Conceptualization, Writing – review & editing, Methodology, Formal analysis, Investigation, Data curation. **Elizabeth Meins:** Writing – review & editing, Formal analysis, Writing – original draft, Data curation, Supervision.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2025.106297.

Data availability

This study was preregistered: https://osf.io/wqz73/?view_only=9b294d8e908d42508e3cf847547b7e61. The associated data files will be available via the Open Science Framework.

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