We know that we don't know:

Children's understanding of common ignorance in a coordination game

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Highlights

- Common ground is typically defined as what people know together (common knowledge).
- It should also include what they do not know together (common ignorance).
- We tested children's ability to use four common knowledge/ignorance states.
- 4- to 8-year-olds played a novel coordination game with a partner.
- The common ignorance states were more difficult than the common knowledge states.

Abstract

Common ground is the knowledge, beliefs, and suppositions shared between partners in an interaction. Previous research has focused extensively on what partners know they know together, i.e., "common knowledge." However, another important aspect of common ground is what partners know they do not know together, i.e., "common ignorance." A new coordination game was designed to investigate children's use of common ignorance. Without communicating or seeing each other's decisions, 4- to 8-year-olds needed to make the same decision as their partner about whether to try to retrieve a reward. To retrieve it, at least one of them needed to know a secret code. The knowledge/ignorance of both partners was ostensively manipulated by showing one, both, or neither partner the secret code in four conditions: common knowledge (both knew the code), common ignorance (neither knew the code), common privileged self knowledge (only children knew the code), and common privileged other knowledge (only their partner knew the code). Children's decisions, latency, and uncertainty were coded. Results showed that the common ignorance states were generally more difficult than the common knowledge states. Unexpectedly, children at all ages had difficulty coordinating when their partner knew the code but they themselves did not (common privileged other knowledge). This study shows that along with common knowledge, common ignorance and common privileged self and other knowledge also play important roles in coordinating with others, but may develop differently.

Keywords: common ground, common knowledge, common ignorance, coordination game

Common ground is the collection of knowledge, beliefs, and suppositions which are shared between participants in an interaction (Clark, 1996): everything we know that we both know together (Tomasello, 2010). On a personal level, common ground may be built from co-presence in an event or actively shared experiences over time (Clark & Marshall, 1978). From a broader perspective, common ground can range from assumptions about what people typically find salient and interesting, to how rational people act in certain situations, to shared, cultural knowledge of facts, values, etc. (Levinson, 1995).

Common ground facilitates interpersonal coordination (Chwe, 2013; Clark, 1996). Rousseau (1754/1984)’s classic scenario of the stag hunt is commonly used to illustrate the challenges of coordination (Skyrms, 2004): Two hunters could either hunt a stag (a high-risk but high-value option that may or may not be available) together, or separately each hunt a rabbit (a low-risk but low-value option, always available). To minimize risk and maximize reward, it is crucial for the two hunters to achieve coordination by searching their common knowledge – a part of their common ground – about whether there is a stag present. When both hunters have common knowledge that the stag is present, the most rational decision is to hunt the stag together. Without this common knowledge, the rational decision is that each hunts a rabbit on their own.

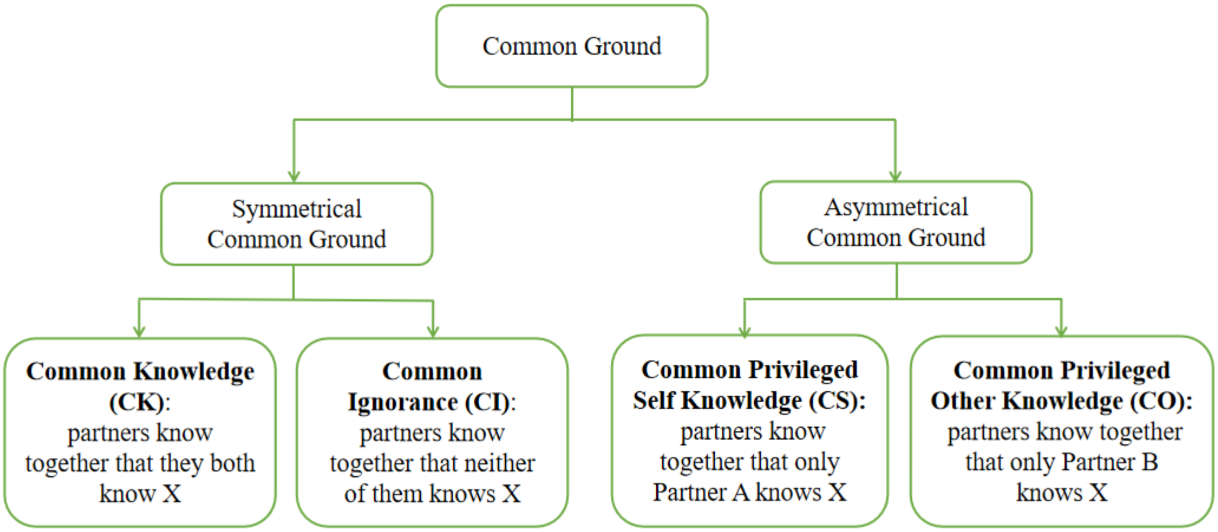
Fleshing Out Common Ground

We propose that there are two components of common ground that should be distinguished: the common awareness and the common content. Common awareness is the state in which both partners know together that they and their partner know something, and the common content is what is known by both partners. Thus, in the case of the stag hunt, if both hunters know that *they both know* that there is something in the field (common awareness), and both know that *the thing* *in the field is a stag* (common content), they are in a common ground situation of common knowledge.

However, what if the content is not known, or is only known by one of the partners? Almost all previous literature has used the terms common ground and common knowledge interchangeably.[1] However, we propose that common ground is actually more complicated than just common knowledge, and that, depending on whether the common content is or is not known by both partners, a fuller picture of common ground should also include notions of "common ignorance" and "asymmetrical common ground" (see Figure 1).

Figure 1

Fleshing out the Notion of Common Ground. 'X,' below, is the Common Content, 'Partner A' is the Self, and 'Partner B' is the Other.



Based on whether the *common content* is or is not known by the partners in an interaction, common ground can consist of "known knowns" (common knowledge) or "known unknowns"

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[1] There are also terminological confusions about related terms: Researchers use different terms, such as "shared knowledge" (Gorman et al., 2013), "mutual knowledge" (e.g., Horton & Keysar, 1996; Schiffer, 1972), "common knowledge" (e.g., Lewis, 1969), and "common belief" (e.g., Brown, 1995; Monderer & Samet, 1989) to refer to common ground or common knowledge.

(common ignorance). Common ignorance is when both partners know that they both do not know something. In the stag hunt example, common ignorance would correspond to a situation in which, for example, it is very foggy in the woods so both hunters are aware that neither of them knows whether the stag is there.

However, in common ground situations there can also be asymmetrical content, i.e., when only one of the partners knows the content and both partners are aware of this: *common privileged knowledge*. For instance, in the stag hunt example, it is possible that one hunter has a better view than the other, and that this is known by both. Thus, they both know together that one knows something that the other does not know. Depending on who has this knowledge and the agents’ perspective, this asymmetrical common ground can be either “common privileged self knowledge” (we both know that I know but you don’t know), or “common privileged other knowledge” (we both know that I don’t know but you know).

In summary, all symmetrical and asymmetrical common ground situations have the same dual structure of common awareness and common content. The differences exist in the content, i.e., in who knows or does not know what.

Common Knowledge and Coordination

The importance of common knowledge has been shown in various other artificial coordination games in addition to the stag hunt scenario. For example, Thomas and colleagues (2014) manipulated whether partners had common knowledge to investigate whether that affected participants’ decisions to coordinate. Adults were invited to play the role of either a butcher or a baker and could choose to work alone or to coordinate with their partner to sell hotdogs (if the hotdog price of the day was high enough). Participants were more likely to choose to coordinate when they had common knowledge with their partner (e.g., the hotdog price of the day was broadcasted by a loudspeaker) compared to other conditions in which they were unsure whether they had common knowledge with their partner (e.g., the message was delivered by an unreliable messenger).

The stag hunt and other coordination games have been adapted for children. Previous studies have demonstrated three main ways in which children can solve coordination problems: via communication, recursive thinking, or saliency.

Communication. As early as 4-7 years of age, children can use verbal (Duguid et al., 2014) and non-verbal (Siposova et al., 2018; Wyman et al., 2013) communication to achieve common knowledge and solve the stag hunt dilemma. For example, Wyman and colleagues (2013) showed that even minimal communication could build up common knowledge about the presence of the cooperative option (the ‘stag’) in the game. Four-year-old children had the option of playing alone to win a simple sticker, or coordinating with their partner to win a shiny sticker if their partner chose to play with them (but they would win nothing if their partner chose not to play with them). If children received a sharing look (i.e. eye contact and a smile) from their partner at the moment of the decision, they were more likely to take the risk and coordinate with their partner. In a similar type of game, just a communicative look from the partner (with raised eyebrows but no smile) led 5-year-olds to choose to coordinate more than when they received a non-communicative look (Siposova et al., 2018).

As Chwe (2001) proposed, coordination problems are trivially easy to solve with verbal or nonverbal communication, which allows social partners to quickly align their decisions to coordinate. This is in part because communication allows “overtness” or “openness” which simplifies the problem of social coordination (Enfield, 2006; Sperber & Wilson, 1986). However, communication is not always available. When there is no means to communicate verbally or non-verbally, individuals can still often solve coordination problems by recursive thinking and saliency.

Recursive Thinking. In coordination games, individuals need to think about what the other is likely to do in order to make their own decision. This kind of thinking back and forth between self and other, known as "recursive thinking", is a potential means by which to achieve coordination non-communicatively (Grueneisen et al., 2014). However, recursive thinking is highly costly in terms of cognitive processing: To think recursively in a coordination game one needs to "read the mind of a mind reader" (De Freitas et al., 2019, p. 1). Grueneisen and colleagues (2014) found that 6-year-olds are able to think recursively to achieve coordination with others. They asked children to work in pairs to choose the same box (out of four) as their partner to win the gummy bears inside. Three of the boxes had two gummy bears drawn on them, and one had four gummy bears drawn on it. Children were each separately told that the only box that contained four gummy bears was one of the boxes drawn with two gummy bears, not the box drawn with four gummy bears, and that they were the only ones who knew this, not their partner. Children chose the box that was drawn with four gummy bears significantly more often when they had to choose the same box as their partner than when playing alone. This was despite knowing that there were only two gummy bears in that box, because they thought that their partner would likely choose this box based on the visible representation of four gummy bears on the box. Thus, 6-year-olds can think recursively about what their partners know, and what their partner knows about what they know (Grueneisen et al., 2014).

Saliency. It has been suggested that although recursive thinking is in principle available to us at all times, whenever possible we solve coordination problem by making assumptions based on simpler options in order to save cognitive resources (Enfield, 2006). To achieve non-communicative coordination, all we need is that all individuals converge on the same choice (Lewis, 1969). Partners may use salience to conform with each other's choices (Schelling, 1960). For example, in Schelling's (1960) "heads or tails" study, each participant was asked to choose to write down either "heads" or "tails" individually. They would win a reward if they wrote down the same thing as the others. Among the 42 participants, there were 36 who chose "heads" while only 6 chose "tails"; thus participants appeared to recognize that "heads" would likely be the more salient choice in this game.

From 5 years of age, children can also use various types of saliency to solve coordination problems. For example, Grueneisen and colleagues (2015a) showed that, to coordinate with their partner without communication, 5-year-olds, but not 3-year-olds, chose the most perceptually-salient box (the only box that had a picture of celery on it), instead of one of three more appealing boxes (boxes that had a picture of ice cream on them). Furthermore, Grueneisen et al. (2015b) showed that 5-year-olds chose the option that a majority had previously chosen. And Goldvicht-Bacon and Diesendruck (2016) found that 5-year-olds can also strategically use common cultural knowledge with their partner (e.g., an Israeli flag with a Hebrew speaker) as a focal point to solve a coordination game. In summary, without being able to communicate with their partner, from age 5-6, children can use recursive thinking and saliency to coordinate with others.

Common Ignorance and Coordination

While children's understanding of their own and others' knowledge and ignorance has been investigated extensively from an individual perspective (what one *or* what the other knows/does not know; e.g., Call & Carpenter, 2001; Goupil et al., 2016; Kim et al., 2016; Liszkowski et al., 2008; Rohwer et al., 2012), common ignorance in coordination games (what we do not know together) has been neglected. Common or individual ignorance situations may demand specific types of intervention or remedial strategies that are not needed when we have common knowledge. For instance, if we realize together that we do not know something, this might lead us to remedy common ignorance by changing this knowledge state. For example, when a couple wants to return to their parked car, if both partners remember where it is, there is little to think about. If one partner does not remember where it is, this might require the extra step of verifying that their partner has the required information. However, if neither remembers where they parked their car, this may pose more of a problem. They will have to try to change their common ignorance by retracing their previous steps together, or each look for the car in different places, or think together about where they usually park, etc.

However, in other cases, people may wish to deliberately maintain their common ignorance, and even intentionally to seek this state of not knowing something together. For example, if two friends are interested in watching the finale of a TV series together on the coming weekend, they may agree together to avoid any form of spoiler knowledge beforehand to maintain their common ignorance for the expected shared excitement.

The only study we are aware of that specifically included common ignorance as a condition is a recent online study with adults. Deutchman et al. (2021) investigated the role of uncertainty in common knowledge and included a control condition in which participants knew together that nobody in their group knew a relevant piece of knowledge. They found no difference between the common knowledge and common ignorance conditions, as both similarly increased cooperation, and concluded that common ignorance could be considered to be a part of common knowledge.

However, no study has investigated common ignorance in children and whether it develops in parallel with common knowledge. Given the potentially distinctive features of common ignorance situations, it is important to investigate them in their own right, and to do so with children, to investigate whether dealing with ignorance develops differently from dealing with knowledge.

The Present Study

We designed a new non-communicative coordination game that tested the four types of common ground involving knowledge and ignorance (see Figure 1). Children were encouraged to try to win the stickers contained in a sticker box. To open the box and obtain the stickers, two requirements had to be satisfied: 1) both children and their partner should non-communicatively and simultaneously choose to open the sticker box, and 2) at least one of them must know the secret code to unlock the box. The secret code was hidden in another box known as the code box. For each trial of the game, both, one or neither of the participants were shown the contents of the code box, in view of both participants, so that they both knew (had common awareness of) whether the other did or did not know the code (the common content). Then children had to decide whether or not to try to open the box with their partner. We measured children's response correctness as the main measure, and also, as secondary measures, children's latency to respond and any signs of uncertainty that they showed (e.g., hesitating and/or changing their response) as indications of the difficulty of the task for them in each condition.

As this was an exploratory study, we did not have a strong prediction about whether the different types of common ignorance would be of comparable difficulty to the different types of common knowledge, i.e., whether children would begin to coordinate with others successfully in each condition at around a similar age, and whether they would show similar latencies to respond and a similar degree of uncertainty. Previous findings suggest that the earliest age at which children can pass non-verbal coordination games is 4 years (Wyman et al., 2013). Due to the novel and exploratory nature of studying common knowledge, common ignorance, and common privileged knowledge within the same paradigm, we tested a wide age range of participants (4 to 8 years) in order to capture any developmental change.

Method

Participants

Participants were 120 children, with 24 children (12 girls) in each of five age groups: 4-year-olds (*M*=4;7; range = 4;0-4;11), 5-year-olds (*M*=5;5; range = 5;0-5;11), 6-year-olds (*M*=6;7; range = 6;0-6;11), 7-year-olds (*M*=7;6; range = 7;0-7;11), and 8-year-olds (*M*=8;4; range = 8;0-8;10). An additional 23 children were tested but excluded from analyses because of experimenter error (4), refusal to continue with the game (2), parental or other interference (2), and failing the pre-test (see below; 13: five 4-year-olds, three 5-year-olds, five 6-year-olds). Participants were tested in local science centers and nurseries in [blinded location]. No socio-economic or other demographic information was collected.

Design

There were four conditions: *common knowledge* (CK), in which both children and their partner knew the code; *common privileged self knowledge* (CS), in which children knew, but their partner did not know the code; *common privileged other knowledge* (CO), in which children did not know, but their partner did know the code; and *common ignorance* (CI), in which neither children nor their partner knew the code (see Table 1). In all conditions, participants knew whether their partners had or did not have access to the code. Children participated in all four conditions within-subjects, in two blocks containing one trial each of the four conditions, for a total of eight trials of the game. In each block, the conditions were presented in random order, with the specification that the same condition was never presented consecutively across blocks.

Table 1

The Four Common Ground States Tested, as a Factor of Which Partner(s) Knew the Secret Code, with the Corresponding Decision that the Partners Should Make to Coordinate Successfully

	Child knew	**Child was ignorant**
Partner knew	*Common Knowledge (CK)* Correct Response: open the box to receive half of the stickers each	*Common Privileged Other Knowledge (CO)* Correct Response: open the box to receive half of the stickers each
Partner was ignorant	*Common Privileged Self Knowledge (CS)* Correct Response: open the box to receive half of the stickers each	*Common Ignorance (CI)* Correct Response: do not open the box, and instead try to win the stickers in the next trial

In the first three conditions, when at least one of the partners knew the code, the correct response was to open the box and obtain the stickers, since the rule was that it was enough for one partner to know the code to be able to open the box. In contrast, in the common ignorance condition, when neither partner knew the code, the correct response was to choose *not* to open the box in that trial, but rather to save the stickers for the next trial (this rule was explained to both partners). Crucially, children had to make the same choice as their partner about whether to open the sticker box or not to win without communicating with their partner and without being able to see her choice. To succeed in the game, children's tasks were: a) to track whether both, either, or neither partner(s) knew the secret code, and b) to coordinate with their partner by making the same choice to open the sticker box or not, on the basis of their common knowledge or ignorance states.

Materials

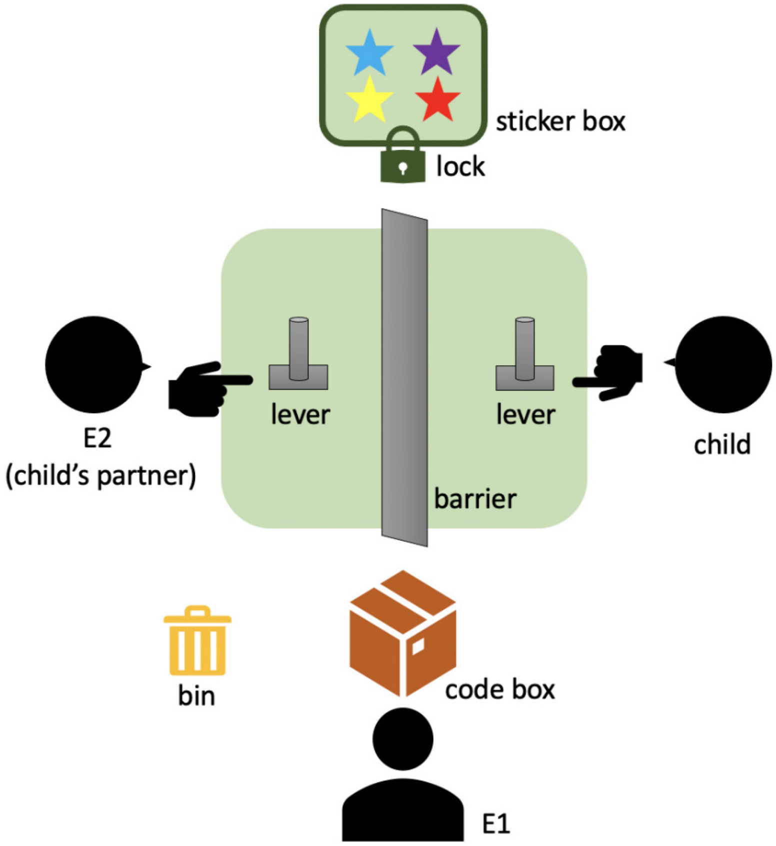
Materials were a sticker box, a code box, a toy rubbish bin, a LEGO board, and multiple sets of four star-shaped foil stickers as rewards (see Figure 2). The sticker box (104 mm × 104 mm) had a transparent lid through which the stickers inside were visible. A drawing of a lock was attached to the lid's edge to remind children that a code was needed to access the stickers. The LEGO board was divided into two sections in the middle by a thin LEGO wall. On each side of the wall was a LEGO lever, one for children and one for their partner, who was a female adult research assistant (E2). Both levers were initially presented in the upright position, and could be pushed forward (towards the sticker box) or backward (away from the sticker box) as a way of indicating whether the decision taken was to open the sticker box or not. The code box was a brown box with a removable lid (90 mm × 90 mm). For each trial of the game, there was a different code (represented by a picture of 1 of 6 fruits, e.g., an apple or a banana) inside the code box. If the lid was open, the code was visible to, and thus known by, whomever it was shown to; if the lid was kept closed, the code was not known. The bin (used to pretend to dispose of any stickers that were not won by the participants) was on the far corner of the table next to the main experimenter (E1).

Procedure

Children were invited to sit facing E2 at a table on their side of the LEGO board. E1 sat to the side next to both of them (see Figure 2). Before participating in the test trials, children went through a training phase in which, after each key rule was explained, children were asked some pre-test questions (see S1) to check their understanding of the rules. While answering these questions, they were also given the opportunity to act out the action for that particular rule. Children who passed each pre-test question continued with the next part of the rule explanation; for those who failed a pre-test question, the explanation and pre-test were repeated. If they still failed that question the second time, their test session was terminated: They were thanked and given some stickers as a thank-you gift for participating.

Figure 2

The Testing Set-up.



Training. E1 introduced E2 and children to each other by name before introducing the rules of the game. Children and E2 were told they were going to play a game as a team, and that the aim of the game was to try to win as many stickers as they could. They were told that they could choose to open the sticker box and get the stickers in there. To do this, they had to show their decision to E1 with their stick (i.e., their lever): If they pushed the stick forward, toward the sticker box, that meant that they chose to open it. If they could open the sticker box, then they would split the stickers with their partner so that each of them would receive two stickers. After explaining each rule, children were asked pre-test questions, to see if they had understood each rule, e.g., "To open the box, what should you do with your sticks?" (see Supplementary Materials section S1 for the full list of pre-test questions). For all pre-test questions in the training phase, children could give their answers verbally or non-verbally, e.g., by moving the lever or nodding or shaking their head.

The code was then introduced, and it was explained that it was needed to open the lock on the sticker box to get the stickers. The code, the picture of a fruit, was contained in the code box that was under the control of E1. Children were told that the code was changed before each trial, and therefore that the partners would know the code only if they were shown the content of the box in that particular trial. E1 explained that she would either show or not show the code to them or to E2. To illustrate this, children watched E1 show E2 the content of the box with the lid open, and ask E2 if she knew the code. E2 said, "Yes, I can see the code, so I know the code."

Children and E2 were then told the next rule: that both partners had to make the same decision in order to get the reward. E1 then explained that the main rule of the game was that as long as one of them, either children or E2, or both of them, knew the secret code, they could open the sticker box as a team. E1 further explained that when neither of them knew the secret code, and therefore they could not open the sticker box, they should choose to push their stick backwards, away from the sticker box. This meant that they chose not to open it in this trial and that the stickers should be saved for later. That is, if they both chose not to open the sticker box, neither partner received anything for that trial, but the stickers remained in the box and were added to the stickers in the next trial, such that, if they both successfully chose to open it in the next trial, each would receive four stickers instead of two.

At the end of the training phase, children were discouraged from communicating with their partner: E1 introduced a no-talking rule by putting her index finger to her lips and saying, "You two can't talk to each other from now on." E1 put up the central wall on the LEGO board and explained, “This barrier will be put up between you, so you guys can’t see each other’s choice.” During the key moments in the procedure, i.e., while E1 showed the code box and while the partners were making their decisions, E2 did not speak to children, make eye contact with them, or make communicative facial expressions to them (though otherwise she behaved in a normal, friendly way). In this way, children and E2 manipulated their sticks independently, behind the barrier, without knowing each other’s decision. E1 explained, “Now, you can’t talk to each other, and you can’t see each other’s decision, but you can still think. You can think: ‘Did you see anything in the code box?’ and ‘Did [E2] see anything in the code box?’ and [E2] will do the same. You two can still make a very good decision as a team.” After a brief verbal reminder of all the main rules of the game, children and E2 were told the game would now begin.

Test. In the test phase, at the beginning of each trial, E1 put a new code in the code box. Depending on the condition of that trial, E1 either showed or did not show the code to children and/or E2 (in randomized order). For example, in the common privileged self knowledge condition, E1 first turned to children and showed them the inside of the box (such that E2 could see that the lid was open but could not see inside the box herself), and then closed the lid, turned towards E2, and showed E2 the box with the lid closed (such that both children and E2 could see the lid was closed). For both the showing and the not showing actions (i.e., both when the lid was open and when it was closed), E1 said, “Take a look!” when holding up the box to children or E2. E1 then returned the code box to its position on the table and said, “Please make your choice to open the sticker box or not,” while alternating gaze between children and E2. To avoid the possibility that children might see cues such as shoulder/arm movements about her choice, E2 always waited to make the correct choice with her stick until after children had made their choice. If children spoke during the test, E2 ignored them, and E1 leaned towards them and whispered, "Remember, no talking. But I think she (E2) didn't hear you, so it's okay."

After both partners had responded, E1 removed the wall blocking their view of their partner's stick and the outcome was shown to them. Then, depending on their responses and the condition they were in, they were either able to retrieve the stickers they had won, or the stickers were either thrown away in the bin by E1 if they had made the wrong decision (including different decisions), or saved in the sticker box if they had made the correct decision not to open the box. When the stickers were correctly retrieved or saved in the box for later, children received positive feedback (e.g., a smile) from both E1 and E2, and E1 said, "Good"; when the stickers had to be thrown away, E1 said, "Sorry" without a smile. In all cases, another set of four stickers was then put into the sticker box for the next trial. This meant that, after a successful common ignorance condition, there were 8 stickers in total at the beginning of the next trial of the game.[2]

In each trial, after children's decision was made and before removing the wall, children were asked "knowledge questions": "Do you know the code?" and "Does she [gesturing to E2] know the code?" These were to check whether they had understood and remembered their own and their partner's knowledge states.

Children were free to stop the game at any point for any reason. At the end of the study, children always received an extra special sticker plus all the stickers they had won during the session. All sessions were videotaped, except for those of three participants, two 7-year-olds and

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[2] A successful common ignorance trial thus meant that the next trial would have double the usual number of rewards, and thus that it might be more motivating for children. On the advice of a reviewer, we checked whether children did better on these trials than on the trials that came after an unsuccessful CI trial, but that was not the case. Chi-square tests showed that the results were not significant either when collapsed across all those conditions/trials, or for any of the six trials separately.

one 8-year-old, due to a technical fault with the video camera. Live-coded response data for these three participants were used in the analyses.

Coding

Children's performance on the pre-test questions and their responses with the stick during the test were manually coded live by E1. In addition, the videotapes were later coded by E1 to confirm the responses and record the latency and signs of uncertainty for each stick decision. No live-coded scores had to be rectified after checking the videos.

The main measure was whether children made the correct choice with their stick in each condition (i.e., response correctness). Children were coded as correct if they pushed their stick towards the sticker box in the CK, CS, and CO conditions, and if they pushed their stick away from the sticker box in the CI condition. If they pushed their stick in one direction, but later changed their decision before the barrier was removed, their final decision was scored.

The latency to make each decision with their stick was also measured, from the moment E1 finished saying, "Please make your choice now," until the stick was pushed such that it touched the platform, or, if it did not touch the platform, when children's hand left the stick. After the first trial of the game, children already knew what to do before the question finished, so some made their choice before the question finished. In those cases, the latency was counted as the minimal latency (i.e., 0.5 second) in the video coding software.

We also coded for signs of uncertainty while children made their decision with the stick. The following were considered to be signs of uncertainty: 1) children put their hand on the stick and pushed it in one direction and changed it at least once to the other direction; 2) children moved their hand towards one side of the stick, then moved it to the other side at least once; 3) children retracted their hand after touching the stick, and retouched it later, or stopped pushing in the middle of the action, and then continued on.

Latency was coded in seconds, and response correctness and signs of uncertainty were each coded as binary outcomes: If children were correct, or showed any sign(s) of uncertainty, this was coded as 1; if they were incorrect, or showed no signs of uncertainty, this was coded as 0.

To assess intercoder reliability, a coder who was naive to the aims of the study independently coded a randomly-selected 20% of the videos in each condition. Reliability was excellent: For correct decision, Cohen’s kappa = 0.95, and for whether children showed signs of uncertainty there was perfect agreement. For latency, there were only 4% of trials (8 out of 192) for which the two coders made judgments leading to more than a 0.5 second difference (the minimal latency captured). All disagreements were easily resolved with discussion.

Analyses: Model Fitting

To investigate which factors contributed to children's performance, we conducted GLMMs (generalised linear mixed models; see S2). For all three dependent variables (response correctness, latency, and signs of uncertainty), eight models were compared with each other. Potential contributing factors were condition (CK, CS, CO, and CI), age (4, 5, 6, 7, and 8 years), gender (male and female), and trial (trial 1 and trial 2). In addition, individual differences were included as a random effect, and the random effects of trial within individual children were included as a random slope. Models varied systematically in whether they included the interaction of condition and age or the main effects of condition and age, and the factor of trial. All models were designed with binomial error structure and logit link function, except the latency models, which were fitted using the gamma distribution and the logarithmic link function gamma error structure.

In model selection, the AIC (Akaike Information Criteria) score (Akaike, 1973) was used to determine the most parsimonious model, balancing data fit and complexity of the model. The best fitted model was selected for each measure by using the model.sel function in R Studio (Version 1.2.1335). Tukey's HSD post hoc tests were used for pairwise comparisons which corrected for family-wise error at a 95% confidence level.

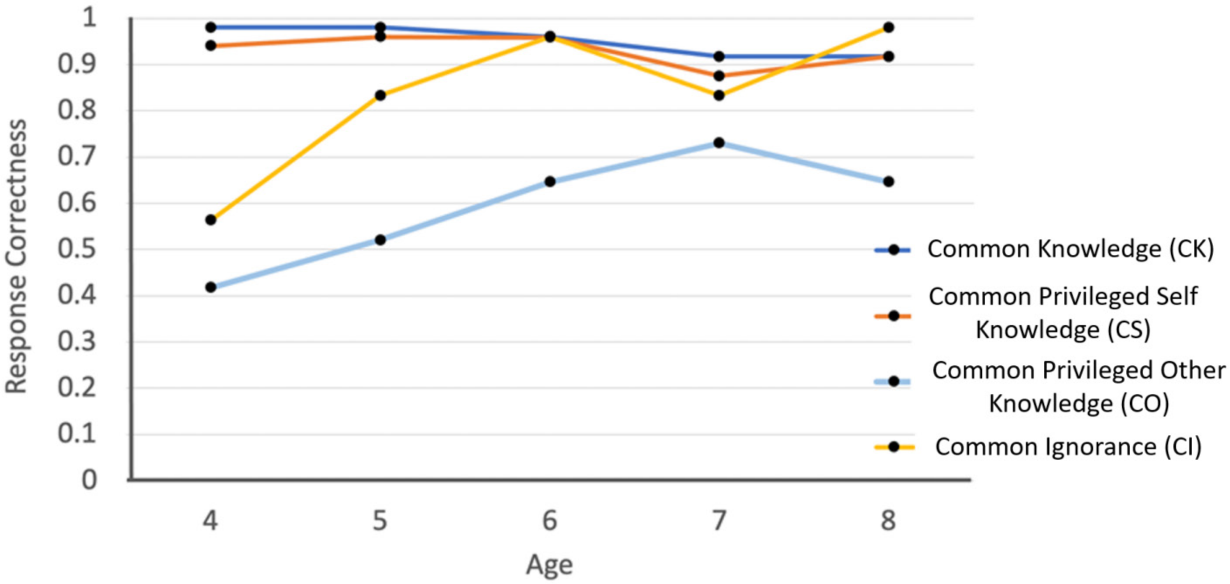
Results

Response Correctness

The main measure was the correctness of children's responses in each condition, i.e. whether children pushed their stick in the correct direction (see Figure 4). As determined by the AIC score, the best of the eight models was a GLMM comprised of the interaction of condition and age, along with the factors of gender and trial, and individual differences (see S2 and S3 for the models for each measure). To test the significance of this full model, we compared its fit with a null model (see S4). The full model improved the fit, $\chi^2(9) = 181.55$, $p < 0.001$ and revealed a significant interaction of condition and age, $\chi^2(7) = 170.38$, $p < 0.001$. Comparing the conditions in post-hoc tests for each age group (collapsed across trials), significant differences were found only for the 4- and 5-year-olds. For 4-year-olds, performance was significantly worse in the CO ($M = 0.42$) than in the CK ($M = 0.98$; $p = 0.008$) and CS ($M = 0.94$; $p < 0.001$) conditions, and was significantly worse in the CI ($M = 0.56$) than in the CS condition ($M = 0.94$; $p = 0.025$). For 5-year-olds, performance was significantly worse in the CO ($M = 0.52$) than in the CK ($M = 0.98$; $p = 0.038$) and CS ($M = 0.96$; $p = 0.011$) conditions. In addition, the best GLMM full model revealed a significant effect of gender, $\chi^2(1) = 3.99$, $p = 0.045$. Boys ($M = 0.85$) performed significantly more correctly than girls (*M* = 0.80). There was also a significant effect of trial, $\chi^2(1) = 9.80$, $p = 0.002$. Performance improved significantly from the first (*M* = 0.79) to the second trial (*M* = 0.86).

Figure 4

Mean Correctness Score Across Both Trials Combined for Each Age Group in Each Condition.



Latency

For latency, the best model was a GLMM comprised of condition, age, trial, and the random effect of individual difference. To test the significance of this full model, we compared its fit with a null model (see S4). The full model improved the fit, $\chi^2(5) = 208.75$, $p < 0.001$. The full model revealed a significant effect of condition, $\chi^2(3) = 16.28$, $p < 0.001$. Children took significantly longer to make their decision in the CO condition (*M* = 2.53 sec) compared to the CK (*M* = 2.14 sec; $p < 0.001$) and CI conditions (*M* = 1.87 sec; $p = 0.03$). There was also a marginally significant effect of age, $\chi^2(1) = 3.83$, $p = 0.050$. Across conditions, 4-year-olds (*M* = 2.79 sec) took longer to respond than 6-year-olds (*M* = 1.93 sec; $p = 0.04$) and 8-year-olds (*M* = 1.78 sec; $p < 0.001$). There was also a significant effect of trial, $\chi^2(1) = 187.67$, $p < 0.001$. Overall, children made their decision significantly more slowly in their first trials (*M* = 3.04) than in their second trials (*M* = 1.17). Please see S5 (Figure S1) for the mean latency at each age in each condition.

Signs of Uncertainty

Children showed very few signs of uncertainty in general. The best model for signs of uncertainty was a GLMM comprised of condition, age, trial, the random effect of individual difference, and the random slope of trial within each individual. Compared with a null model, the full model improved the fit significantly, $\chi^2(7) = 36.09$, $p < 0.001$. The full model revealed a significant effect of condition, $\chi^2(4) = 11.48$, $p = 0.02$. Children showed significantly more signs of uncertainty in the CO condition (*M* = 0.13) than in the CI condition (*M* = 0.06; $p = 0.04$); there were no other significant differences between conditions. There was also a significant effect of trial, $\chi^2(2) = 25.99$, $p < 0.001$). Children showed signs of uncertainty significantly more often in their first trials (*M* = 0.15) than in their second trials (*M* = 0.04). Please see S5 (Figure S2) for the proportion of children who showed signs of uncertainty at each age in each condition.

Post-hoc Analysis: Patterns of Response

We also analyzed the response patterns of children to determine whether they used a particular response strategy consistently across the game and, if so, to explore whether there were any developmental differences in the strategies used. For instance, some children might always choose to open the sticker box, whereas some might choose to make their decision based on their own knowledge state only, instead of trying to coordinate with their partner. If so, this would result in a particular pattern of responses across conditions. By looking at children's response patterns across conditions, we identified the five most common patterns. Always presented in the order common knowledge (CK), common privileged self knowledge (CS), common privileged other knowledge (CO), and common ignorance (CI), and with correct responses noted as 1 and incorrect responses noted as 0, the five most common response patterns were: all correct (i.e., considering both own and other's knowledge/ignorance appropriately in all four conditions; 1-1-1-1), egocentric (i.e., based solely on children's own knowledge/ignorance; 1-1-0-1), always open (i.e., driven by the reward, so always chose to open the sticker box; 1-1-1-0), incorrect when ignorant (i.e., children were correct in their two knowledge conditions but incorrect in their two ignorant conditions; 1-1-0-0), and incorrect when asymmetrical (i.e., children were only correct when they shared the same knowledge/ignorance state as their partner; 1-0-0-1).

Table 2 presents the percentage of children who showed each of these five response patterns at each age. Starting from age 6, the most common response pattern was all correct, with the majority of 6- and 8-year-olds showing this pattern. In contrast, the most common response pattern for the 4- and 5-year-olds was the egocentric response pattern in which they appeared to respond based only on their own knowledge/ignorance. Note, however, that almost as many 5-year-olds showed the all correct response pattern as the egocentric response pattern. Still, less than 60% of children at each age showed the all correct response pattern.

Table 2

The Percentage of Children at Each Age Who Showed Each Response Pattern

Age	**All correct 1-1-1-1**	**Egocentric 1-1-0-1**	**Always open 1-1-1-0**	**Ignorant conditions incorrect 1-1-0-0**	**Asymmetrical conditions incorrect 1-0-0-1**	**Other**
4	12.5	**37.5**	27.1	14.6	6.3	2.1
5	37.5	**41.7**	8.3	6.3	0	6.3
6	**58.3**	29.2	2.1	2.1	2.1	6.3
7	**45.8**	16.7	14.6	2.1	4.2	16.6
8	**54.2**	29.2	0	2.1	0	18.5

Note. Response patterns are in the order: CK-CS-CO-CI, with correct decisions noted as 1 and incorrect decisions noted as 0. In addition to the listed five main response patterns, all age groups also showed other miscellaneous response patterns which are included in the Other column. Each of children's two trials is counted in the percentages. The most common response for each age is highlighted in bold.

Please see S6 for further results concerning children's consistent vs. inconsistent response patterns across trials, and S7 for their responses to the self and other knowledge control questions.

Discussion

In this paper we offer a new theoretical framework and a new experimental paradigm to more comprehensively investigate the notion of common ground. We argued that along with common knowledge (both partners know together that they know something), common ground should also include common ignorance (both partners know together that they do not know something) and asymmetrical knowledge states (both partners know together that only one of them knows something). We investigated the extent to which 4- to 8-year-old children can use these knowledge/ignorance states with their partners in a novel coordination game that required simultaneous responses without communication. Previous studies have investigated children's understanding of common knowledge (e.g., Wyman et al., 2013), but the current study is the first to investigate all four types of common ground systematically within the same paradigm.

We found that children showed different developmental patterns across the four conditions. In the common knowledge（CK) and common privileged self knowledge (CS) conditions, in both of which children knew the code, children performed well from the earliest age we investigated (4 years of age). In contrast, in the common ignorance (CI) condition, in which neither they nor their partner knew the code, they did not perform well at 4 years, instead improving dramatically between 4 to 6 years. The common privileged other knowledge (CO) condition, in which the child did not know the code, but in which their ignorance was compensated for in the game by their partner's knowledge of the code, turned out to be the most difficult condition. In this condition, children improved gradually from 4 to 7 years, but their performance remained relatively poor across all ages. In addition, in this condition, children often took longer and showed more signs of uncertainty when making their decision, which also suggests that this condition was more difficult for them. The analysis of children's response patterns showed similar developmental results: Children's overall performance across the four conditions transitioned at age 6, when the most prevalent response pattern changed from egocentric (following only their own knowledge state) to all correct – though even the older children did not show the all-correct response pattern at very high rates.

Thus the most pronounced difference in difficulty between conditions appeared to be due not so much to whether the conditions involved common knowledge vs. ignorance, or symmetrical vs. asymmetrical common ground, but instead whether children themselves were knowledgeable vs. ignorant. Processing one's own ignorance states in a common ground situation may be more difficult than processing one's own knowledge states to achieve coordination. This difficulty in processing may be indicated by some of the latency and uncertainty findings. That is, the finding that children often spent more time and were more uncertain in the CO condition than in the other conditions suggests that it is unlikely that they were just responding "without thinking," based egocentrically on their own lack of knowledge. Instead, if anything, these results suggest that they may have had to engage in "more thinking" in this condition, even if they did so unsuccessfully and their final decision was erroneous.

One potential explanation for the special difficulty of the CO condition could be that this condition is particularly demanding in terms of response inhibition requirements. For example, something like the double inhibition account proposed by Leslie et al. (2004) to explain performance in avoidance false belief tests may help explain children's difficulty with this condition. We could speculate that children, aware of their ignorance of the code, needed first to inhibit a prepotent tendency to choose to open the box (this would also explain why the CI condition was more difficult than the knowledge conditions, as it also required this initial inhibition of the prepotent response to open the box). However, in the CO condition, to be successful, children would also need to consider their partner's knowledge of the code and cancel that inhibition, or in Leslie and colleagues' terminology, generate an "inhibition of inhibition" (p. 2). This extra step of needing to suppress the initial inhibition was unique to this condition. Children were able to achieve each type of inhibition separately, as demonstrated by their relatively better performance in the CI and CS conditions, but were not able to achieve both together when both were needed. This hypothetical demand of double inhibition could be reflected in the longer latency and increased signs of uncertainty that we found in the CO condition compared to the other conditions.

To further investigate this issue, a study could be designed in which the key rule of the game is changed. Instead of being able to open the sticker box if at least one partner knows the code, the rule could be that they can open the sticker box only if *both of them* know the code. With this new rule, the correct response is to open the sticker box only in the CK condition. In this case, the double inhibition would be in the CS, rather than the CO, condition. That is, to succeed in the CS condition, children would need to inhibit both the bias to open the box and the egocentric bias to use their own knowledge only, so if children performed worse in the CS condition only, this would support the double inhibition account. However, if children still performed worst in the CO condition, it would suggest that there is something difficult about taking into account their partner’s knowledge when they themselves are ignorant, rather than the difficulty lying with the current set-up of the game.

Another future study could consider the social functions of ignorance, and the fact that common ignorance might have two opposite functions in everyday scenarios. Depending on the content and context of ignorance, partners may choose either to avoid or to maintain their common ignorance. In the current version of the game, having common ignorance was undesirable because children could not choose to obtain the reward immediately. In future studies, testing children with a more positive common ignorance scenario in which it would be desirable to not know something together might help to reveal a more complete picture of children’s understanding of common ignorance. For example, instead of the focus of the study being on knowing a secret code, the focus could be on trying to avoid finding out a movie spoiler, so that they can watch the movie and find out how it ends together with their partner. In that case, only when they both know that they do not know the code together can they maximize the enjoyment of watching the movie as a team.

In conclusion, in the current study, we offered a new theoretical framework for common ground that integrates both knowledge and ignorance states of the partners as potential contents of their common awareness, and, based on this, a new coordination game to investigate the development of children's understanding of the different types of common ground situations. Our results showed that the development of common ground understanding may be more complex and extended in time than previously thought, with the states that feature ignorance (whether common or asymmetrical) being particularly difficult to understand. Thus the implicit assumption that common ignorance is just a case of, or can be reduced to, common knowledge may be incorrect. Common ignorance and common knowledge may have different cognitive demands linked to the requirements of different coordination situations. We hope this new theoretical and experimental paradigm will contribute to future studies that further investigate the complexity of common ground understanding in development.

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Supplementary Materials

S1. Script for Training and Testing

Training

[Beginning without the barrier in between the child and their partner, and with the sticker box in the middle of the table.] You two will work together on this game and win some stickers. The stickers are in this sticker box [point to the sticker box]. As you can see, there are one, two, three, four; four stickers in the sticker box. If you both choose to open this box, each of you will get two stickers. [Point to the two sticks on each side of the table in front of them. The sticks start in the position straight up.] You will use these sticks to show your choice of opening the sticker box. You can push forward, like this, if you want to try to open the box [show the action by pushing the stick to the front, i.e. in the direction of the sticker box].

Question: To open the box, what shall you do with your sticks?

As you can see, the sticker box has a lock on it. It needs a code to open it. The code is like apple, or orange [show the code pictures accordingly]. The code will be changed for every round of the game, but it will always be a kind of fruit. The code will be in this code box [take out the code box and show the pictures in there]. For each round of the game, each of you can either know the code or not know the code. You can know the code if I show you the box like this, so you can look inside and see it [open the lid and get both of them to look inside]. Can you see it? Or you will not know the code if I show you the box like this [show both of them the box without opening the lid]. Can you see it now?

Question: If I show [E2's name] the box like this [the box is shown without opening the lid], does [E2's name] know the code?

Question: If I show you the box like this [the box is shown open, with the lid open], do you know the code? [turn to the E2 and ask] Do you think she/he knows the code?

Because you two are working together, if one or both of you knows the code, you can open the lock on the sticker box. For example, if only you know the code, or only [E2's name] does, or both of you know the code, you can open the lock on the sticker box. You don't have to both know the code to open it. But if you [looking at child] don't know, and you [looking at E2] don't know the code, you cannot open the lock on the sticker box. If you try to open the lock on the sticker box without knowing the correct code, you will lose all these stickers [pantomime dumping the stickers into the bin].

Question: If [E2's name] <u>knows</u> the code, and you <u>don't</u> know the code, can you open the lock on the sticker box?

Question: If [E2's name] <u>doesn't</u> know the code, and you <u>don't</u> know the code either, can you open the lock on the sticker box?

Question: If nobody knows the code, but both of you push the stick to the front to choose to open the sticker box, what will happen?

But you can also choose not to open this box, and in that case you will not get any stickers. If you don't want to open the box, you push the stick backward [show the action by pushing the stick to the back, away from the box]. Because you two are working together, you both have to make the same decision of pushing the sticks either forward or backward [show two sticks the same direction together]. If you both make the same decision, I can open the box for you, so you can get two stickers each [open the sticker box, and point to the stickers in there]; or I will not open the box for you but save the stickers for you until the next round [gently pat the sticker box]. However, if you make different decisions, I don't know what to do. Then you two will lose all the stickers in the box, like this – see, they get thrown away [open the box, and dump all the stickers into the rubbish bin].

Question: So if [E2's name] does this [push the stick to the front], and you push it to the back [push the stick to the back], can I open the box? What will happen? How about if [E2’s name] does this, and you do this [the sticks are pushed in the opposite directions]? What will happen?

Right, if neither of you knows the code, you don’t want to choose to open the sticker box because then you’ll lose all those stickers! So when you both don’t know the code, you can both choose to push the stick back to tell me that you don’t want to open the box for this round, you want to save those stickers for later. In that way, the stickers will be saved in the sticker box, and not be dumped. So you can try to win them in the next round of the game. That way, for the next round, you will have even more stickers in the box to win [put four more stickers in the box]. See? If no one knows the code, and both of you push the stick to the back, you can win more stickers in the next round of the game!

Question: If neither of you knows the code, what should you do with the sticks?

Question: If both of you push the stick backward, can you get any stickers in this round? Will you lose the stickers in the box?

Okay, there is this one last, important rule of this game. During the whole rest of the game, you two cannot talk to each other [put index finger to lips]. If you talk, you will lose all the stickers for this round of the game [pantomime dumping the stickers into the bin]. And this barrier will be put up between you; then you cannot see each other’s sticks [take out the barrier and put it in the middle]. So, for each round of the game, you have to decide on your own what to do with the stick. But keep in mind what your partner will be choosing too! You two can still make a good decision based on what you have seen or not, and you have seen whether the other has seen or not. Okay, we're ready to get started! Let me just remind you again of the rules: You two have to make the same decision in order to not lose any stickers: either push the stick this way to open the box or push the stick back this way to not open the box. To open the sticker box, at least one of you needs to know the code for the lock, by seeing it here in this code box. You both don't need to know the code to open the sticker box, only one of you needs to know it. Remember, no talking! Otherwise your stickers will be taken for this round of the game!

Testing. If you are ready [look questioningly at both], the game starts now! Here is the sticker box, and here is the code box. A new code has been put in there. [Pick up the code box, and turn towards one of them. The order of turning to children vs. E2 first is counterbalanced across trials. Conditions are administered in counterbalanced order too. For example, here the child will receive the CS condition first.] Take a look. [Open the lid towards one of them; after they look inside the box, close the lid, and then turn it towards the other.] Take a look. [Show the box with the lid on towards them. After they look, put the code box down in the middle of the table, in front of E1.] Okay, if you know the code, please remember it and use it later. Please decide now whether you choose to open the sticker box or not, and show me your choice with the stick. [E2 always makes her choice after children.] Okay, decisions have been made and cannot be changed anymore. [To child:] Do you know the code? Does [E2] know the code? Now, let's see if you made the same choice or not! [Take the barrier away.] [Possible responses:]

- Good, you two made the same choice of opening the box. Please tell me the code. Good, each of you can get two stickers from the sticker box! [Open the sticker box and split the stickers between them.]

- Good, you two made the same choice of not opening the box. You cannot get any stickers for this round, but your stickers will be saved for the next round of the game! [Gently pat the lid of the sticker box.]
- Sorry, you two made different choices, you cannot win any stickers in this round! We have to throw them away. [Dump the stickers in the rubbish bin.]

[Refill the sticker boxes with four more stickers in all cases. Place a new code in the code box.]

Shall we go for another round of the game? The code to open the sticker box has now been changed. [Place the barrier back in the middle of the child and E2, and take out the code box again for the next round.]

S2. Model Fitting

Screenshots of the eight models that were fitted for each measurement.

a) response correctness

```
#R Model fitting----

mod1 <- glmer(Response ~ Age*Condition + as.factor(Trial)+ (1|ParticipantNumber) ,
              data = Data1,
              family = binomial(link = "logit"))

mod2 <- glmer(Response ~ Age*Condition + Gender + as.factor(Trial)+ (1|ParticipantNumber) ,
              data = Data1,
              family = binomial(link = "logit"))

mod3 <- glmer(Response ~ Age + Condition + as.factor(Trial) + (1|ParticipantNumber) ,
              data = Data1,
              family = binomial(link = "logit"))

mod4 <- glmer(Response ~ Age + Condition + Gender + as.factor(Trial) + (1|ParticipantNumber) ,
              data = Data1,
              family = binomial(link = "logit"))

mod5 <- glmer(Response ~ Age*Condition + Gender + as.factor(Trial) + (1|ParticipantNumber) + (0 + Trial|ParticipantNumber),
              data = Data1,
              family = binomial(link = "logit"))

mod6 <- glmer(Response ~ Age + Condition + Gender + as.factor(Trial) + (1|ParticipantNumber) + (0 + Trial|ParticipantNumber),
              data = Data1,
              family = binomial(link = "logit"))


mod7 <- glmer(Response ~ Age*Condition + as.factor(Trial) + (1|ParticipantNumber) + (0 + Trial|ParticipantNumber),
              data = Data1,
              family = binomial(link = "logit"))

mod8 <- glmer(Response ~ Age + Condition  + as.factor(Trial) + (1|ParticipantNumber) + (0 + Trial|ParticipantNumber),
              data = Data1,
              family = binomial(link = "logit"))
```

b) latency

```
#L Model fitting----

mod1_L <- glmer(Latency ~ Age*Condition + as.factor(Trial)+ (1|ParticipantNumber) ,
              data = Data1,
              family = Gamma(link = "log"))

mod2_L <- glmer(Latency  ~ Age*Condition + Gender + as.factor(Trial)+ (1|ParticipantNumber) ,
              data = Data1,
              family = Gamma(link = "log"))

mod3_L <- glmer(Latency  ~ Age + Condition + as.factor(Trial) + (1|ParticipantNumber) ,
              data = Data1,
              family = Gamma(link = "log"))

mod4_L <- glmer(Latency  ~ Age + Condition + Gender + as.factor(Trial) + (1|ParticipantNumber) ,
              data = Data1,
              family = Gamma(link = "log"))

mod5_L <- glmer(Latency  ~ Age*Condition + Gender + as.factor(Trial) + (1|ParticipantNumber) + (0 + Trial|ParticipantNumber),
              data = Data1,
              family = Gamma(link = "log"))

mod6_L <- glmer(Latency  ~ Age + Condition + Gender + as.factor(Trial) + (1|ParticipantNumber) + (0 + Trial|ParticipantNumber),
              data = Data1,
              family = Gamma(link = "log"))

mod7_L <- glmer(Latency  ~ Age*Condition + as.factor(Trial) + (1|ParticipantNumber) + (0 + Trial|ParticipantNumber),
                data = Data1,
                family = Gamma(link = "log"))

mod8_L <- glmer(Latency  ~ Age + Condition + as.factor(Trial) + (1|ParticipantNumber) + (0 + Trial|ParticipantNumber),
                data = Data1,
                family = Gamma(link = "log"))
```

c) signs of uncertainty

```
#U Model fitting----

mod1_U <- glmer(Uncertainty ~ Age*Condition + as.factor(Trial)+ (1|ParticipantNumber) ,
              data = Data1,
              family = binomial(link = "logit"))

mod2_U <- glmer(Uncertainty ~ Age*Condition + Gender + as.factor(Trial)+ (1|ParticipantNumber) ,
              data = Data1,
              family = binomial(link = "logit"))

mod3_U <- glmer(Uncertainty ~ Age + Condition + as.factor(Trial) + (1|ParticipantNumber) ,
              data = Data1,
              family = binomial(link = "logit"))

mod4_U <- glmer(Uncertainty ~ Age + Condition + Gender + as.factor(Trial) + (1|ParticipantNumber) ,
              data = Data1,
              family = binomial(link = "logit"))

mod5_U <- glmer(Uncertainty ~ Age*Condition + Gender + as.factor(Trial) + (1|ParticipantNumber) + (0 + Trial|ParticipantNumber),
              data = Data1,
              family = binomial(link = "logit"))

mod6_U <- glmer(Uncertainty ~ Age + Condition + Gender + as.factor(Trial) + (1|ParticipantNumber) + (0 + Trial|ParticipantNumber),
              data = Data1,
              family = binomial(link = "logit"))

mod7_U <- glmer(Uncertainty ~ Age*Condition  + as.factor(Trial) + (1|ParticipantNumber) + (0 + Trial|ParticipantNumber),
                data = Data1,
                family = binomial(link = "logit"))

mod8_U <- glmer(Uncertainty ~ Age + Condition  + as.factor(Trial) + (1|ParticipantNumber) + (0 + Trial|ParticipantNumber),
                data = Data1,
                family = binomial(link = "logit"))
```

d) memory check for self knowledge

```
#S Model fitting----

mod1_S <- glmer(Self ~ Age*Condition + as.factor(Trial)+ (1|ParticipantNumber) ,
                data = Data1,
                family = binomial(link = "logit"))

mod2_S <- glmer(Self ~ Age*Condition + Gender + as.factor(Trial)+ (1|ParticipantNumber) ,
                data = Data1,
                family = binomial(link = "logit"))

mod3_S <- glmer(Self ~ Age + Condition + as.factor(Trial) + (1|ParticipantNumber) ,
                data = Data1,
                family = binomial(link = "logit"))

mod4_S <- glmer(Self ~ Age + Condition + Gender + as.factor(Trial) + (1|ParticipantNumber) ,
                data = Data1,
                family = binomial(link = "logit"))

mod5_S <- glmer(Self ~ Age*Condition + Gender + as.factor(Trial) + (1|ParticipantNumber) + (0 + Trial|ParticipantNumber),
                data = Data1,
                family = binomial(link = "logit"))

mod6_S <- glmer(Self ~ Age + Condition + Gender + as.factor(Trial) + (1|ParticipantNumber) + (0 + Trial|ParticipantNumber),
                data = Data1,
                family = binomial(link = "logit"))

mod7_S <- glmer(Self ~ Age*Condition + as.factor(Trial) + (1|ParticipantNumber) + (0 + Trial|ParticipantNumber),
                data = Data1,
                family = binomial(link = "logit"))

mod8_S <- glmer(Self ~ Age + Condition + as.factor(Trial) + (1|ParticipantNumber) + (0 + Trial|ParticipantNumber),
                data = Data1,
                family = binomial(link = "logit"))
```

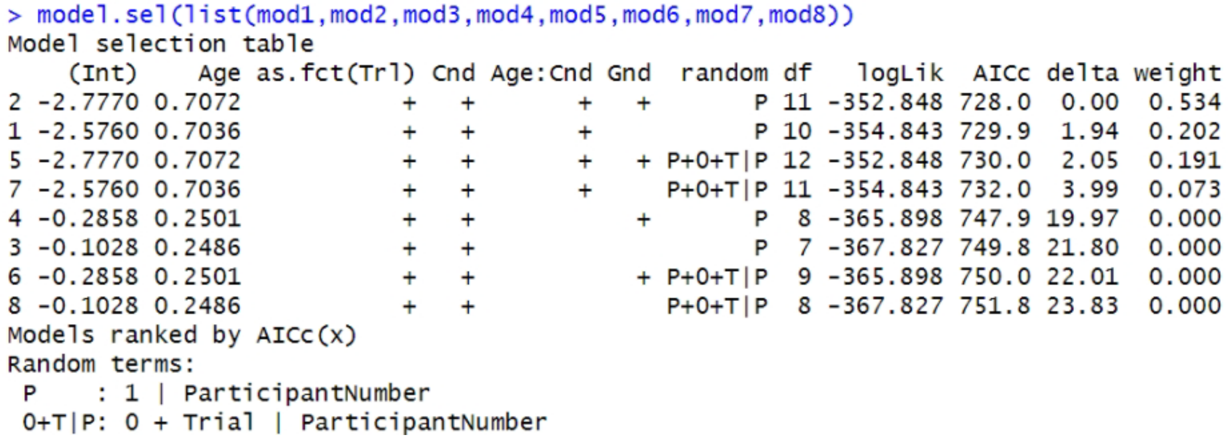
e) memory check for other knowledge

```
#O Model fitting----
mod1_O <- glmer(Other ~ Age*Condition + as.factor(Trial)+ (1|ParticipantNumber) ,
                data = Data1,
                family = binomial(link = "logit"))

mod2_O <- glmer(Other ~ Age*Condition + Gender + as.factor(Trial)+ (1|ParticipantNumber) ,
                data = Data1,
                family = binomial(link = "logit"))

mod3_O <- glmer(Other ~ Age + Condition + as.factor(Trial) + (1|ParticipantNumber) ,
                data = Data1,
                family = binomial(link = "logit"))

mod4_O <- glmer(Other ~ Age + Condition + Gender + as.factor(Trial) + (1|ParticipantNumber) ,
                data = Data1,
                family = binomial(link = "logit"))

mod5_O <- glmer(Other ~ Age*Condition + Gender + as.factor(Trial) + (1|ParticipantNumber) + (0 + Trial|ParticipantNumber),
                data = Data1,
                family = binomial(link = "logit"))

mod6_O <- glmer(Other ~ Age + Condition + Gender + as.factor(Trial) + (1|ParticipantNumber) + (0 + Trial|ParticipantNumber),
                data = Data1,
                family = binomial(link = "logit"))

mod7_O <- glmer(Other ~ Age*Condition + as.factor(Trial) + (1|ParticipantNumber) + (0 + Trial|ParticipantNumber),
                data = Data1,
                family = binomial(link = "logit"))

mod8_O <- glmer(Other ~ Age + Condition + as.factor(Trial) + (1|ParticipantNumber) + (0 + Trial|ParticipantNumber),
                data = Data1,
                family = binomial(link = "logit"))
```

S3. Model Selection

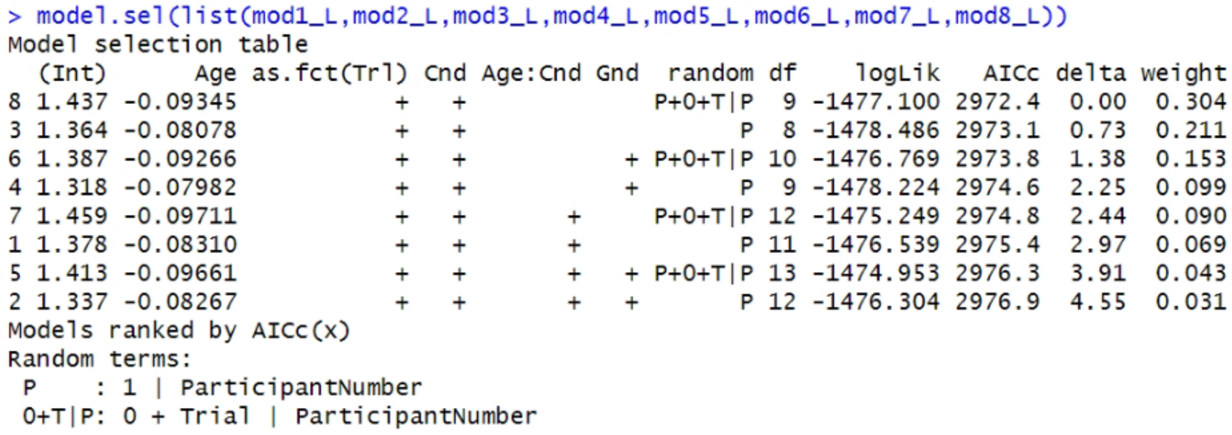
Screenshots of the results output from the eight fitted models for each measurement. The best model for each data set was the one with the lowest AIC score among the eight.

a) response correctness



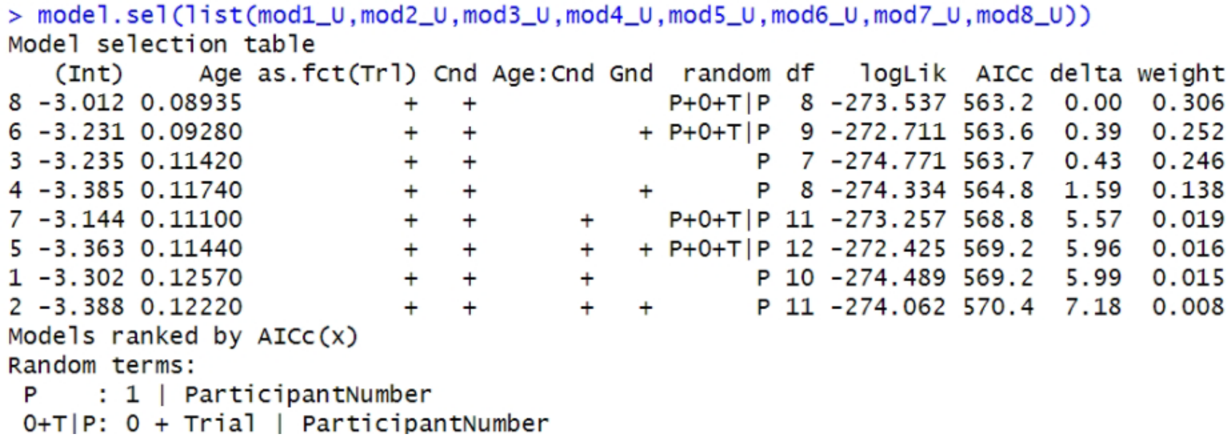
```
> model.sel(list(mod1,mod2,mod3,mod4,mod5,mod6,mod7,mod8))
Model selection table
    (Int)    Age as.fct(Trl) Cnd Age:Cnd Gnd  random df   logLik  AICc delta weight
2 -2.7770 0.7072           +   +       +   +       P 11 -352.848 728.0  0.00  0.534
1 -2.5760 0.7036           +   +       +           P 10 -354.843 729.9  1.94  0.202
5 -2.7770 0.7072           +   +       +   + P+0+T|P 12 -352.848 730.0  2.05  0.191
7 -2.5760 0.7036           +   +       +     P+0+T|P 11 -354.843 732.0  3.99  0.073
4 -0.2858 0.2501           +   +           +       P  8 -365.898 747.9 19.97  0.000
3 -0.1028 0.2486           +   +                   P  7 -367.827 749.8 21.80  0.000
6 -0.2858 0.2501           +   +           + P+0+T|P  9 -365.898 750.0 22.01  0.000
8 -0.1028 0.2486           +   +             P+0+T|P  8 -367.827 751.8 23.83  0.000
Models ranked by AICc(x)
Random terms:
 P    : 1 | ParticipantNumber
 0+T|P: 0 + Trial | ParticipantNumber
```

b) latency



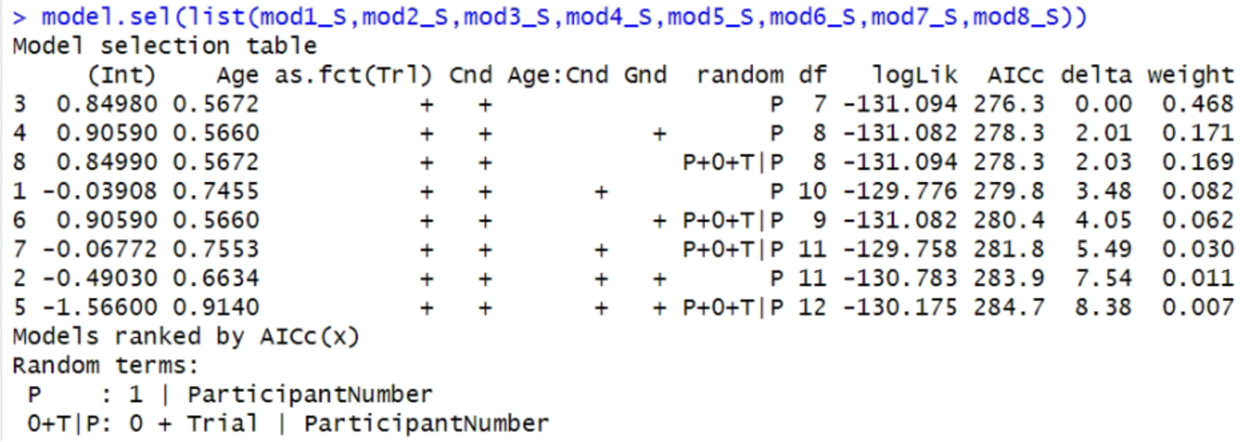
```
> model.sel(list(mod1_L,mod2_L,mod3_L,mod4_L,mod5_L,mod6_L,mod7_L,mod8_L))
Model selection table
  (Int)      Age as.fct(Trl) Cnd Age:Cnd Gnd  random df    logLik   AICc delta weight
8 1.437 -0.09345           +   +             P+0+T|P  9 -1477.100 2972.4  0.00  0.304
3 1.364 -0.08078           +   +                   P  8 -1478.486 2973.1  0.73  0.211
6 1.387 -0.09266           +   +           + P+0+T|P 10 -1476.769 2973.8  1.38  0.153
4 1.318 -0.07982           +   +           +       P  9 -1478.224 2974.6  2.25  0.099
7 1.459 -0.09711           +   +       +     P+0+T|P 12 -1475.249 2974.8  2.44  0.090
1 1.378 -0.08310           +   +       +           P 11 -1476.539 2975.4  2.97  0.069
5 1.413 -0.09661           +   +       +   + P+0+T|P 13 -1474.953 2976.3  3.91  0.043
2 1.337 -0.08267           +   +       +   +       P 12 -1476.304 2976.9  4.55  0.031
Models ranked by AICc(x)
Random terms:
 P    : 1 | ParticipantNumber
 0+T|P: 0 + Trial | ParticipantNumber
```

c) signs of uncertainty



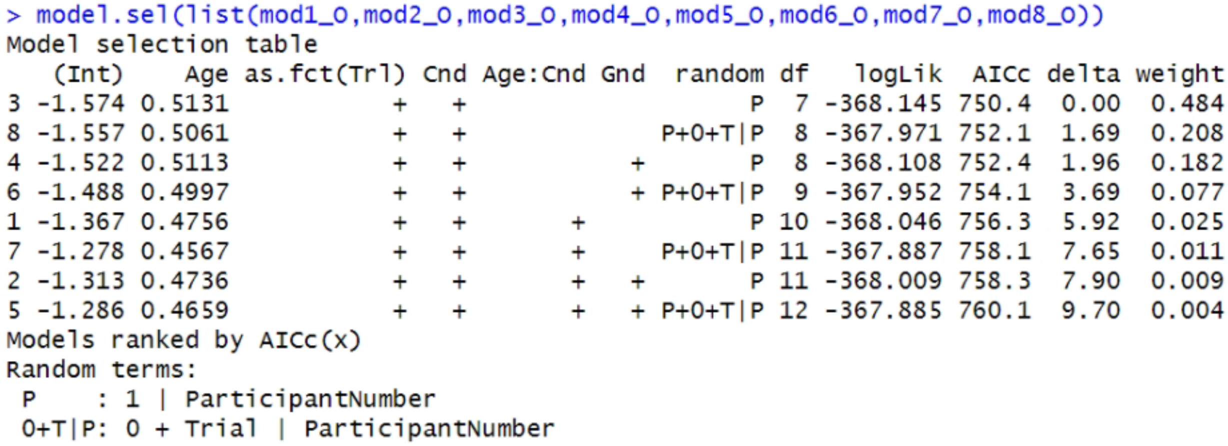
```
> model.sel(list(mod1_U,mod2_U,mod3_U,mod4_U,mod5_U,mod6_U,mod7_U,mod8_U))
Model selection table
   (Int)     Age as.fct(Trl) Cnd Age:Cnd Gnd  random df   logLik  AICc delta weight
8 -3.012 0.08935           +   +             P+0+T|P  8 -273.537 563.2  0.00  0.306
6 -3.231 0.09280           +   +          + P+0+T|P  9 -272.711 563.6  0.39  0.252
3 -3.235 0.11420           +   +                   P  7 -274.771 563.7  0.43  0.246
4 -3.385 0.11740           +   +          +       P  8 -274.334 564.8  1.59  0.138
7 -3.144 0.11100           +   +       +     P+0+T|P 11 -273.257 568.8  5.57  0.019
5 -3.363 0.11440           +   +       +   + P+0+T|P 12 -272.425 569.2  5.96  0.016
1 -3.302 0.12570           +   +       +           P 10 -274.489 569.2  5.99  0.015
2 -3.388 0.12220           +   +       +   +       P 11 -274.062 570.4  7.18  0.008
Models ranked by AICc(x) 
Random terms:
 P    : 1 | ParticipantNumber
 0+T|P: 0 + Trial | ParticipantNumber
```

d) memory check for self knowledge



```
> model.sel(list(mod1_S,mod2_S,mod3_S,mod4_S,mod5_S,mod6_S,mod7_S,mod8_S))
Model selection table
     (Int)    Age as.fct(Trl) Cnd Age:Cnd Gnd  random df   logLik  AICc delta weight
3  0.84980 0.5672           +   +                   P  7 -131.094 276.3  0.00  0.468
4  0.90590 0.5660           +   +          +       P  8 -131.082 278.3  2.01  0.171
8  0.84990 0.5672           +   +             P+0+T|P  8 -131.094 278.3  2.03  0.169
1 -0.03908 0.7455           +   +       +           P 10 -129.776 279.8  3.48  0.082
6  0.90590 0.5660           +   +          + P+0+T|P  9 -131.082 280.4  4.05  0.062
7 -0.06772 0.7553           +   +       +     P+0+T|P 11 -129.758 281.8  5.49  0.030
2 -0.49030 0.6634           +   +       +   +       P 11 -130.783 283.9  7.54  0.011
5 -1.56600 0.9140           +   +       +   + P+0+T|P 12 -130.175 284.7  8.38  0.007
Models ranked by AICc(x) 
Random terms:
 P    : 1 | ParticipantNumber
 0+T|P: 0 + Trial | ParticipantNumber
```

e) memory check for other knowledge



```
> model.sel(list(mod1_O,mod2_O,mod3_O,mod4_O,mod5_O,mod6_O,mod7_O,mod8_O))
Model selection table
   (Int)    Age as.fct(Trl) Cnd Age:Cnd Gnd  random df   logLik  AICc delta weight
3 -1.574 0.5131           +   +                   P  7 -368.145 750.4  0.00  0.484
8 -1.557 0.5061           +   +             P+0+T|P  8 -367.971 752.1  1.69  0.208
4 -1.522 0.5113           +   +           +       P  8 -368.108 752.4  1.96  0.182
6 -1.488 0.4997           +   +           + P+0+T|P  9 -367.952 754.1  3.69  0.077
1 -1.367 0.4756           +   +       +           P 10 -368.046 756.3  5.92  0.025
7 -1.278 0.4567           +   +       +     P+0+T|P 11 -367.887 758.1  7.65  0.011
2 -1.313 0.4736           +   +       +   +       P 11 -368.009 758.3  7.90  0.009
5 -1.286 0.4659           +   +       +   + P+0+T|P 12 -367.885 760.1  9.70  0.004
Models ranked by AICc(x)
Random terms:
 P    : 1 | ParticipantNumber
 0+T|P: 0 + Trial | ParticipantNumber
```

S4. Predictors in the Best Model and Results

Table S1

Response Correctness: Generalized Linear Mixed Model: Binomial Error Distribution

Variable	Model	Predictor	χ^2	*df*	*p*
Response	GLMM	Full-null	181.55	9	< 0.001 ***
		Condition×Age	170.38	7	< 0.001 ***
		Gender	3.9897	1	= 0.045 *
		Trial	9.8024	1	= 0.002 **

*Note. Full model: Response ~ Condition*Age + Gender + as.factor(Trial) + (1|ParticipantNumber). Null model: Response ~ 1 + (1|ParticipantNumber). Levels of the factors: Condition: CK, CS, CO, CI; Age: 4- to 8-year-olds; Gender: male, female; Trial: 1, 2.* *** *p* <.001. ** *p* <.01. * *p* <.05.

Table S2

Latency*: Generalized Linear Mixed Model: Gamma Error Distribution*

Variable	Model	Predictor	$\chi2$	*df*	*p*
Latency	GLMM	Full-null	208.75	5	< 0.001 ***
		Condition	16.28	3	< 0.001 ***
		Age	3.83	1	= 0.03
		Trial	187.67	1	< 0.001 ***

Note. Full model: Latency ~ Condition + Age + as.factor(Trial) + (1|ParticipantNumber). Null model: Latency ~ 1 + (1|ParticipantNumber). Levels of the factors: Condition: CK, CS, CO, CI; Age: 4- to 8-year-olds; Gender: male, female; Trial: 1, 2. *** *p* <.001.

Table S3

***Signs of Uncertainty**: Generalized Linear Mixed Model: Binomial Error Distribution*

Variable	Model	Predictor	$\chi2$	*df*	*p*
Signs of Uncertainty	GLMM	Full-null	36.09	7	< 0.001 ***
		Condition	11.48	4	= 0.04 *
		Age	4.69	2	= 0.37
		Trial	25.99	2	< 0.001 ***

*Note. Full model: Uncertainty ~ Condition + Age + as.factor(Trial) + (1|ParticipantNumber) + (0+Trial|ParticipantNumber). Null model: Uncertainty ~ 1+ (1|ParticipantNumber) + (0+Trial|ParticipantNumber). Levels of the factors: Condition: CK, CS, CO, CI; Age: 4- to 8-year-olds; Gender: male, female; Trial: 1, 2. *** p <.001. ** p <.01. * p <.05.*

S5. Further Results: Latency and Signs of Uncertainty at Each Age

Figure S1

Mean Latency at Each Age in Each Condition.

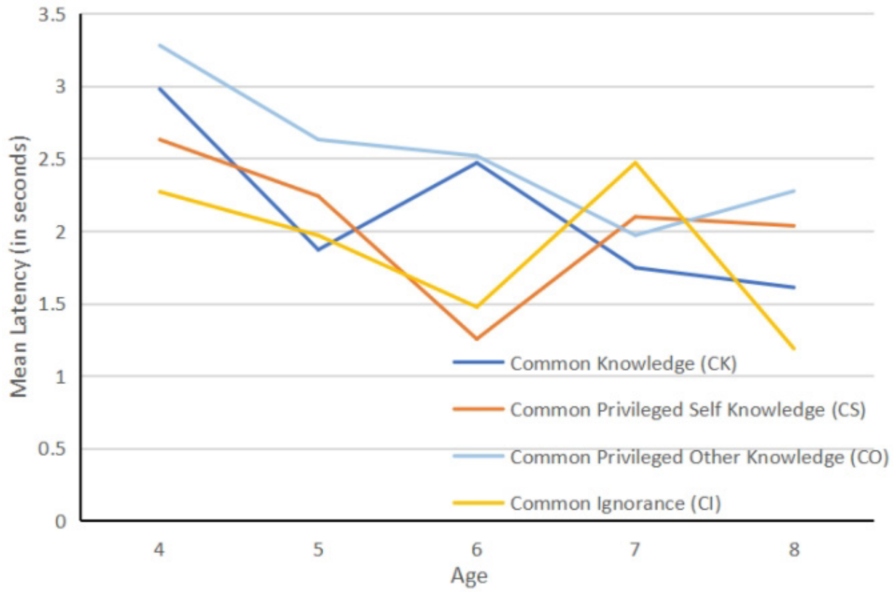
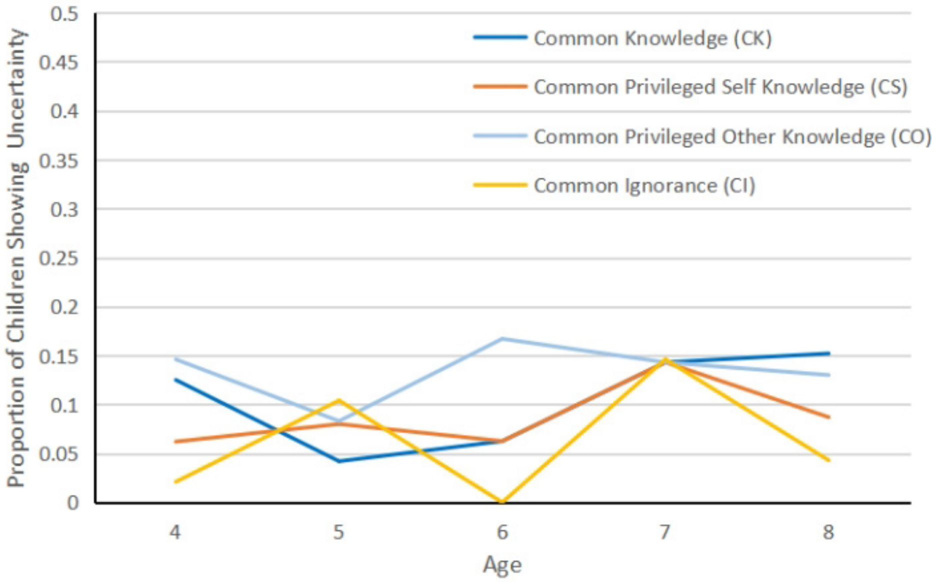


Figure S2

Proportion of Children Who Showed Signs of Uncertainty at Each Age in Each Condition.



S6. Consistent vs. Inconsistent Response Patterns Across Trials

Table S4 shows the percentage of children who showed consistent vs. inconsistent response patterns across the two trials at each age. Among the percentage of children who improved here, 4-year-olds were the only age group that mostly changed their answers to other types of response rather than to the all correct response.

Table S4

Percentage of Children Who Showed Consistent vs. Inconsistent Response Patterns Across the Two Trials at Each Age

Age	**Consistent**	**Inconsistent**
4	37.5%	62.5% (4.2% improved)
5	41.7%	58.3% (41.7% improved)
6	66.7%	33.3% (29.2% improved)
7	29.2%	70.8% (41.7% improved)
8	50%	50% (29.2% improved)

Note. "Improved" means children who changed from their previous response in the first trial to all correct in the second trial.

S7. Self and Other Knowledge Questions

We asked children questions about their own and their partner’s knowledge state after their response in each trial, to check whether they had taken the correct knowledge states into account in their decision making. For the self knowledge question (“Do you know the code?”), children were coded as correct if they nodded or verbally said, “Yes” in the CK and CS conditions, and if they shook their head or verbally said, “No” in the CI and CO conditions. For the other knowledge question (“Does she [E2] know the code?”), children were coded as correct if they nodded or verbally said, “Yes” in the CK and CO conditions, and if they shook their head or verbally said, “No” in the CI and CS conditions. For intercoder reliability, Cohen’s kappa = 0.99 for the self knowledge question, and Cohen’s kappa = 0.96 for the other knowledge question. The disagreements were easily solved with discussion.

Self Knowledge Questions. Children’s responses to the self knowledge questions (see Figure S3) were best accounted for by a GLMM on condition, age, trial, and the random effect for individual differences. To test the significance of this full model, we compared its fit with a null model (see Table S5 for the model). The full model improved the fit, $\chi^2(7) = 47.03, p < 0.001$. The full model for the self knowledge question revealed a significant effect of condition, $\chi^2(3) = 19.55$, $p < 0.001$. Children answered significantly more correctly in the CK condition ($M = 0.99$) than in the CI ($M = 0.93$; $p = 0.005$) and CO ($M = 0.93$; $p = 0.01$) conditions. There were no significant age differences for the self knowledge questions: At each age children responded at near-ceiling levels in all conditions. There was also a significant effect of trial, $\chi^2(1) = 24.05$, $p < 0.001$. Children performed worse in their first trials than in their second trials (first trial: $M = 0.93$, second trial: $M = 0.98$).

Table S5

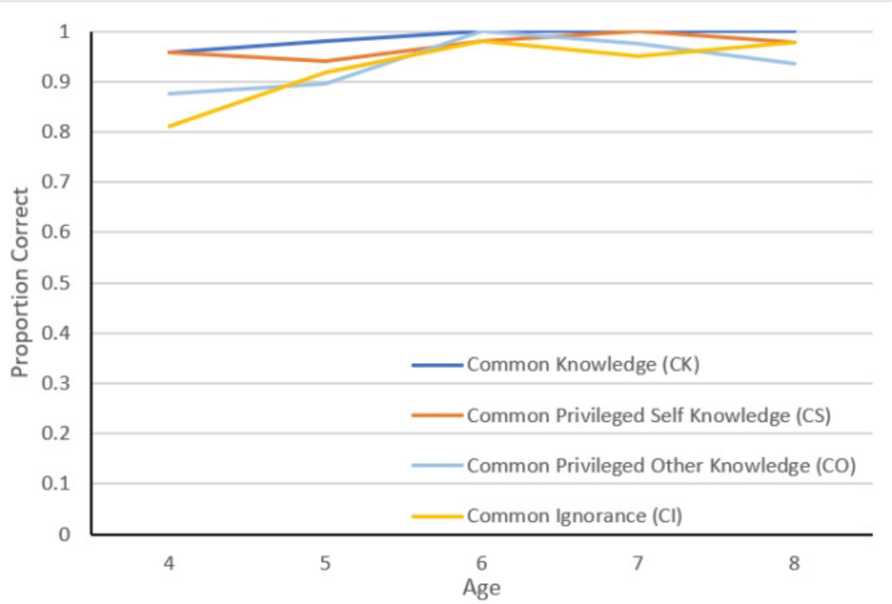
***Memory Check for Self Knowledge**: Generalized Linear Mixed Model: Binomial Error Distribution*

Variable	Model	Predictor	χ^2	*df*	*p*
Self Knowledge	GLMM	Full-null	47.03	5	< 0.001 ***
		Age	3.42	1	= 0.06
		Condition	19.55	3	< 0.001 ***
		Trial	24.05	1	< 0.001 ***

*Note. Full model: Self ~ Age + Condition + as.factor(Trial)+ (1|ParticipantNumber). Null model: Self ~ 1 + (1|ParticipantNumber). Levels of the factors: Age: 4- to 8-year-olds; Condition: CK, CS, CO, CI; Gender: male, female; Trial: 1, 2. *** p <.001. ** p <.01. * p <.05.*

Figure S3

Proportion of Children Who Correctly Answered the Self Knowledge Question at Each Age in Each Condition.



Other Knowledge Questions. Children's responses to the other knowledge questions (see Figure S4) were best accounted for by a GLMM on condition, age, trial, and the random effect for individual differences. To test the significance of this full model, we compared its fit with a null model (see Table S6 for the model). The full model improved the fit, $\chi^2(7) = 49.56$, $p < 0.001$. There was no difference across conditions for the other knowledge questions, $\chi^2(3) = 1.3$, $p = 0.72$. There was a significant effect of age, $\chi^2(1) = 19.85$, $p < 0.001$. Four-year-olds ($M = 0.72$) performed significantly worse than 6-year-olds ($M = 0.91$; $p = 0.002$) and 8-year-olds ($M = 0.92$; $p = 0.002$), and 5-year-olds ($M = 0.72$) performed significantly worse than 6- and 8-year-olds (p's $= 0.004$ and 0.003, respectively). There was also a significant effect of trial, $\chi^2(1) = 58.83$, $p < 0.001$. Children performed worse in their first trials than in their second trials (first trial: $M = 0.74$, second trial: $M = 0.91$).

Table S6

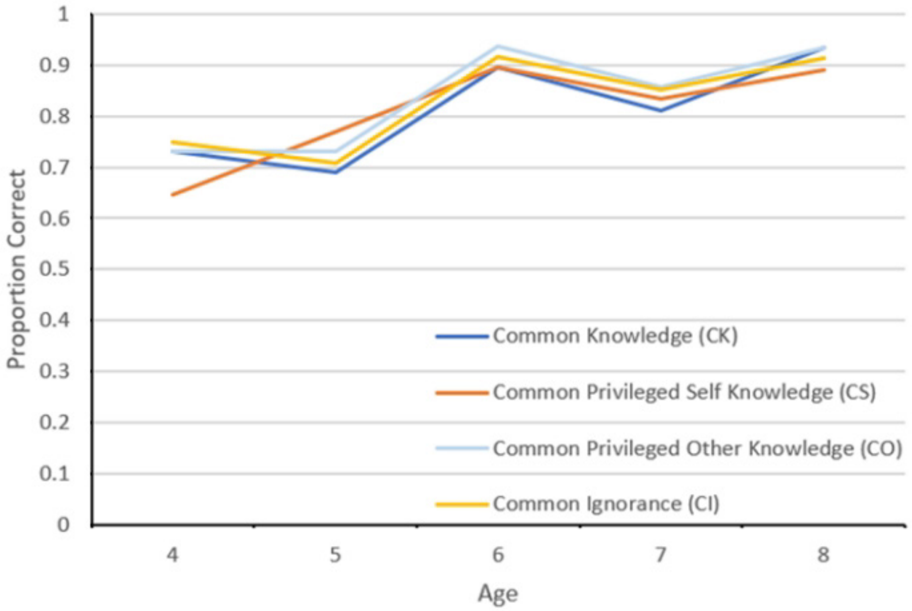
***Memory Check for Other Knowledge**: Generalized Linear Mixed Model: Binomial Error Distribution*

Variable	Model	Predictor	χ^2	*df*	*p*
Other Knowledge	GLMM	Full-null	79.56	5	< 0.001 ***
		Age	19.85	1	< 0.001 ***
		Condition	1.30	3	= 0.72
		Trial	58.83	1	< 0.001 ***

*Note. Full model: Other ~ Age + Condition + as.factor(Trial)+ (1|ParticipantNumber). Null model: Other ~ 1 + (1|ParticipantNumber). Levels of the factors: Age: 4- to 8-year-olds; Condition: CK, CS, CO, CI; Gender: male, female; Trial: 1, 2. *** p <.001. ** p <.01. * p <.05.*

Figure S4

Proportion of Children Who Correctly Answered the Other Knowledge Question at Each Age in Each Condition.



Children's performance in these two knowledge questions might provide an explanation for the dip in performance in the CO condition. That is, although children's performance at all ages on both questions was very good, the younger children were not always accurate in reporting their partner's knowledge/ignorance state. Descriptively, we found that 4-year-olds performed particularly poorly when answering questions about their partner's knowledge state in the CO condition, i.e. when they knew the code but their partner was ignorant. Issues with attention and/or memory might partially account for the youngest children's tendency to overestimate their partner's knowledge state in the CO condition.