

## Supporting Information for Online Publication Only

### Appendix S1

#### Story stimuli for fMRI task

Eight stories in Mental, Social, and Physical conditions were used in the fMRI task. The probe sentence (see Methods in the main text) is italicized.

< Mental >

1. One day a pirate told Jimmy about a hidden treasure. The pirate thought that the treasure was buried behind Jimmy's house. Jimmy believed him. So Jimmy dug a big hole behind his house, but he didn't find a treasure. Jimmy soon realised the pirate didn't know where the treasure was. *Jimmy was mad. He had done all that work for nothing.*
2. Today Sam is giving a surprise birthday party for his friend Eric. Sam invited Eric to come over and play basketball. Sam wanted to keep the party a secret, so he didn't wish Eric a happy birthday. Eric thought that Sam forgot about his birthday and was very upset. *Eric was happy when he found out that Sam threw him a birthday party.*
3. A poor fisherman lived in an old shack with his wife. One day the fisherman was very surprised: the fish he caught started talking. The fish promised to grant the man a wish. The fisherman's wife wanted a new a house, but she did not believe that they would get a new house from a fish. *But the next day the fisherman and his wife had a beautiful house.*
4. Emil's mother sent him to the lake to gather fish for dinner. Emil was scared of going to the lake alone. He thought that there was a sea creature living in the lake. Emil's mother knew that the sea creature was really Emil's own reflection. She told Emil to smile at the creature. *Emil smiled into the river and saw a face smiling back.*
5. One day two girls were walking through the forest. They saw a troll with a long beard lying near a rock. The girls thought the troll's beard was stuck under the rock. They cut the troll's beard to set him free. The girls were surprised: the troll was angry with them for ruining his beard. *The troll wasn't stuck. He was sleeping.*
6. Before leaving camp, Molly drew a picture of herself to give to her friend Clara. Clara found the picture, and didn't know it was a picture of Molly. She labeled the picture "scary monster" as a joke. When Molly saw the writing on the picture she was angry at Clara. *Molly and Clara had a long talk and now they're friends again.*
7. One day, everyone in the world turned purple. That morning, people looked at each other, and wondered if they were dreaming. Everybody was shocked. Even the smartest scientists didn't know

what had happened. But Jimmy wasn't surprised at all; he knew the secret. *Someone had put purple pills in the city's water.*

8. The Hardy boys were worried because they were running late. Their Dad wanted them to come home early. Joe saw a shortcut on the map. The boys looked carefully at the road. The entrance to the shortcut was hidden by trees. They knew they could easily have missed it. *Frank, one of the boys, turned their car down the dark dirt road.*

<Social>

1. One night Mary's parents brought Mary to sleep at her grandmother's house. Grandma was very old and went to bed early. So Mary started playing in her grandmother's closet. In the back of the closet, was a pair of beautiful red shoes. Mary put them on. *All of a sudden, Mary wasn't in the closet any more.*
2. Sarah and Lori play together on the school soccer team. Sarah usually plays offense. She runs up and down the field and scores goals. Lori is the team's goalie. She is very good at catching the ball when the other team kicks it at the goal. Today the school has a big game but Lori is sick. *Sarah has to play goalie because Lori is too sick to play soccer.*
3. Once upon a time, a girl and her little brother went out into the field to pick flowers. The day was very hot and the little brother got very thirsty. On the walk back home he drank from a puddle. But the puddle had a curse on it. After drinking, the boy turned into a baby goat. *The big sister found a spell to turn the goat back into a boy.*
4. Once there lived a musician. She was so good at playing the flute that when she played everyone immediately started dancing. They couldn't stop dancing until she stopped playing. One night a burglar came to rob the musician's house. She was practicing her flute, so the burglar started to dance. *The burglar danced until the police came.*
5. Jenny and Samantha were twins. They lived in a big city with their parents. For two weeks during their summer vacation they went to visit their Granpa. They stayed at Granpa's house near the lake. Every morning Granpa and the girls went swimming or sailing. *Jenny and Samantha both came home strong and tanned.*
6. Chenma lived with her only son, Jhe, in a forest in Shanxi Province. Jhe was one of the tiger hunters. Jhe's father taught him how to hunt tigers. But Jhe's father had died. The money from selling tiger meat, skin and bones, was barely enough to keep Jhe and Chenma warm and fed. *One day, Chenma's son went to the woods to find a tiger.*
7. Old Mr McFeegle is a gray wrinkled old farmer, who wears grey wrinkled old clothes and gray wrinkled old boots. Georgie is Mr McFeegle's nephew from town. One day, Georgie put on Mr

McFeeble's gigantic boots. The boots were so big, Georgie disappeared inside them. *Mr McFeeble looked everywhere, but couldn't find Georgie.*

8. There once was a poor woodsman who had a huge and oily sausage hanging under his nose. The sausage was so long that it hung from the woodsman's nose all the way down to his toes. No matter how he tugged at the sausage, pulled it and even cut it, the sausage would not budge. *The sausage just hung in front of him everywhere he went.*

< Physical >

1. One day, a little robin landed on a huge, strange-looking tree, and ate one of its berries. This was a magical tree that had special powers. In the spring, the robin laid three eggs. Soon, two of the eggs cracked and little robins came out. But the last egg did not crack for a long time. *When the last egg cracked a beautiful firebird came out.*
2. Two houses stood side by side in a village. One house was made of wood and the other was made of brick. The wooden house was very tall and thin. The brick house was short and fat. One night a big storm came to the village. In the morning only the brick house was still standing. *The wooden house fell down during the storm.*
3. In the cooking school there was a big batch of dough on the windowsill in a covered pot. The sun shone onto the pot all day long. The dough sat on the counter and got bigger and bigger. Pretty soon the dough grew bigger than the pot. It grew and grew, all over the windowsill. *A few hours later, the whole room was full of dough.*
4. In the tiny town of Chewandswallow it rained or snowed three times each day. Once during breakfast, once during lunch and once during dinner. But it never rained rain and never snowed snow. It rained things like soup and juice and snowed things like mashed potatoes. *Yesterday it snowed meatballs for dinner in Chewandswallow.*
5. Once there was a palace, surrounded by a large garden. But although the weather was perfect and the soil was dark and moist, nothing grew there. Plants in the garden produced neither flowers nor fruit. There were so few leaves on the trees that there was no shade anywhere. *The garden was empty because of a magic curse.*
6. The house on the corner was very creepy. The windows were full of cobwebs, the roof was crooked, and the door hung partly open. The wind whistled through the holes in the grey walls, making a low wailing sound, especially when there was a full moon or a storm coming. *Sometimes, lights inside the house flashed on and off all night.*
7. In the attic was a strange old map of a small island in the middle of the sea. The scratchy drawing showed that there were forests and cliffs on the island. There were many twists and turns in the beach,

and one long river. About halfway up the river, the map was marked with a big “X”. *The ‘X’ marked the spot where a treasure was buried.*

8. The school was all ready for the first day of class. The desks and chairs were lined up in perfect rows and columns. On each desk was a pile of neatly stacked books. But right before the first day of class a pipe broke in the bathroom. Water flooded the entire school. *The desks and chairs floated in the hallways.*

### **Theory of Mind behavioral battery – ToM booklets**

Two booklets contained 44 questions, belonging to one of 14 categories. Booklet 1 was about children in the same class look for their books for reading time, and Booklet 2 was about a family spending a day out in the park. Each page in both books had flaps (under which small magnet pieces could be hidden) and magnet pieces of books, people, and other objects described in the story. The experimenters memorized the full script and were trained to tell the story realistically, rather than simply reciting the script. Children were encouraged to give verbal responses to the questions, and also to place the magnet pieces in the appropriate place on the booklet page. In many questions, we asked for both the child’s prediction (e.g., Which book is she going to choose?) and the explanation (e.g., Why do you think so?). Here we describe 12 questions from Booklet 1 and 2 questions from Booklet 2, to give an example of questions in each of the 14 categories. Example 1-12 are from Booklet 1, 13-14 are from Booklet 2. Explanation questions which were used as our main measure and coding criteria for scoring children’s explanations are in **bold** font.

1. Common Desires: Sam is going to pick a book off the table. One book is about bicycles, and the other one is about fire trucks. Which book do you think Sam wants? The one about bicycles or the one about fire trucks? Can you tell me why?
2. Diverse Desires: Now here is Laura. Laura is going to pick a book off the bookshelf. There is a book that has pictures of fish in the ocean, and there is a book that has pictures of dinosaurs. What do you like better, fish or dinosaurs? You do? That’s great! But Laura likes [other one] better. Can you guess which book Laura is going to choose? Will she pick the book about fish or about dinosaurs? How do you know?
3. Diverse Beliefs: Jonathan is looking for his book. His book might be under the table, or it might be behind the reading chair. Where do you think the book is? That’s a good idea! But guess what? Jonathan thinks his book is [the other one]. Where will Jonathan look for his book? Will he look under the table or behind the chair?

4. Ignorance: Here is Alex. Alex hasn't found his book on skiing. That's because Alex's book is in the cupboard under the sink. See, here it is. But Alex hasn't looked in the cupboard yet; he's looking at the bookshelf. Does Alex know where his book is?
5. Easy Reference (common ground/perspective taking): Here is Ryan, coming in the door. Look, here on the bookshelf right in front of Ryan is a big book about airplanes! And there's another book about airplanes, over here, on the cabinet, behind Ryan's back. Now Ryan says "I want that book about airplanes!" Which book do you think Ryan wants? **How do you know it's that one? (correct if the child mentions that Ryan is looking at the book, is facing the book, or that the book is in front of him).**
6. False Belief Reality Unknown: Here is Grace. She's outside now, but soon she will be coming inside to look for her favorite butterfly book. Grace thinks that her butterfly book is in the toy bin. But look, there's no butterfly book in the toy bin! When Grace comes in, where do you think Grace is going to look first for her butterfly book?
7. False Belief Reality Known: This morning when he came to school, Ethan put his book above the coat hooks. What color is Ethan's book? That's right! But while he was outside playing, Ethan's book fell down behind the coats. See here is Ethan's book behind the coats. Then Paul came in - and Paul put his book above the coat hooks. See here's Paul's book above the coat hooks. What color is Paul's book? That's right! But Ethan was still outside playing, so he didn't see Paul come in. So he doesn't know that this is Paul's book right here. Now, when Ethan comes in from outside, where will he look first for his book? Oh look, here is Ethan reaching for Paul's book from the coat hooks. **Why is Ethan trying to take Paul's book? (correct if the child mentions that Ethan thinks the book is his).**
8. Emotion: (continued from Q.7) Here comes Paul. Paul can see Ethan trying to take his book. Paul feels very sad. **Why does Paul feel sad? (correct if the child mentions that the book is Paul's)**
9. Moral Judgment: (continued from Q.8) Is Ethan being mean and naughty for taking Paul's book? Should Ethan get in trouble with the teacher for taking Paul's book? Can you give Paul back his book? Now can you help Ethan find his own book? Where is Ethan's book really?
10. False Belief based on Expectation: William always likes to read the book about mountains. The mountain book has pictures of mountains and the plants that live in the mountains. It's a big grey book. Every day this month, the mountain book was on the carpet. But today, Mr. Abott moved the mountain book over to the shelf, and put a new book on the carpet. This book is also grey, but it's a different book, about horses. When William comes in, and sees this book on the carpet, what will he think is inside - pictures of mountains or pictures of horses? **Why will he think that? (correct if the child refers to William's past or his expectations).**

11. **Hard Reference:** Here is Daniel. Earlier today Daniel was reading this book about fruit. He really liked the section about oranges. It had pictures of oranges, orange juice, orange trees, and even the farmers who grow the oranges. Now Daniel is coming in to get a book. Here on the table is the book about fruit. Over here, on the shelf, is a book about history, with an orange cover. Daniel says "I want the orange book!" Which book does Daniel want? **How do you know? (correct if the child mentions the orange section).**
12. **Interpretation:** Chloe is playing a game today: she is trying to be completely silent all day long. So when she wants to say something, she draws a picture instead of talking. Right now, Chloe wants Mr. Abbott to get a book down from the top shelf for her. Up on the top shelf is a book about witches, and a book about boats. Chloe wants the book about witches, but she doesn't know how to draw a witch. On one piece of paper she draws a witch's hat like this. On another piece of paper she draws a witch's broom like this. But she has to choose just one. Which picture should Chloe give to Mr. Abbot, so he will get her the book about witches and not the book about boats? **Why is this one better than that one? (correct if the child mentions sailboat's resemblance to the hat).**
13. **Emotion Reminder:** Last week, when they came to the park, a black puppy was playing with Sprint. He was very friendly. But then during snack time last week, the black puppy stole Ivan's cookie, and ran away with it! Now, while the kids are having their snack today, Sprint is running around, playing with the same friendly black puppy. The black puppy comes running over to the kids, wagging his tail. How will Ivan feel when he sees the black puppy today? [Will he feel happy or sad?] Will Ivan go over near the puppy, or will he go far away from the puppy? **Why will he do that? (correct if the child mentions Ivan's past experience with the puppy).**
14. **Moral False beliefs:** Now the games are over, and it's almost time to go home. Mother tells the kids to find all of their toys; they have to bring them all home. Joshua brought his toy truck with him to the park, but now he can't find it. He's looking everywhere but he can't find it. Then Isabel find the toy truck. But she doesn't tell anyone. While no one is looking, she takes the toy truck, and buries it in the sandbox. So Joshua looks everywhere and he can't find his toy truck. Mother gets mad at Joshua, because he lost his truck. How does Joshua feel? Is Joshua mad at Isabel? **Why (why not)?** Is Mother mad at Isabel? **Why (why not)? (correct if the child mentions that Joshua or Mother does not know that Isabel hid the truck).**

## Results

Table S1.

*Comparison of Mean Percent Signal Change (PSC) in Each ROIs in Children and Adults. No ROI Showed a Difference in the Response Amplitude Between Children and Adults.*

	Mean PSC: Children	Mean PSC: Adults	T	df	<i>p</i>
Right TPJ	0.81	0.57	0.92	23	0.37
Left TPJ	0.89	0.67	1.49	19	0.15
PC	0.27	0.32	-0.31	17.3	0.76
dMPFC	0.78	0.53	1.33	16	0.20
mMPFC	0.85	0.14	1.73	12	0.11
vMPFC	1.21	0.70	1.06	12	0.31

*Note.* ROI = region of interest; TPJ = temporo-parietal junction; PC = precuneus; MPFC = medial prefrontal cortex; dMPFC = dorsal MPFC; mMPFC = middle MPFC; vMPFC = ventral MPFC.

Table S2.

*Average Accuracy (SD) for all 14 Categories, Collapsing Across Prediction and Explanation Questions in the ToM Behavioral Battery. N/A Indicate That There Were no Questions in this Category in the Given Response Format.*

Category	Prediction Accuracy (SD)	Explanation Accuracy (SD)
Common Desire	1.00 (0.00)	N/A
Diverse Desire	0.95 (0.22)	N/A
Diverse Belief	1.00 (0.00)	N/A
Ignorance	1.00 (0.00)	N/A
Easy Reference	0.80 (0.41)	0.70 (0.47)
Hard Reference	0.60 (0.50)	0.56 (0.51)
False Belief Reality Known	0.99 (0.11)	0.97 (0.18)
False Belief Reality Unknown	0.95 (0.23)	N/A
False Belief based on Expectation	0.97 (0.16)	0.85 (0.38)
Moral False Belief	0.89 (0.32)	0.90 (0.31)
Emotion Reminder	0.80 (0.41)	1.00 (0.00)
Emotion	N/A	1.00 (0.00)
Moral Judgment	1.00 (0)	N/A
Interpretation	0.90 (0.30)	0.87 (0.34)

Figure S1.

Average Selectivity Index in six ROIs in children and adults (Children: N=10, Adults: N=8). Note that the ROIs were not identified in all of the participants (see main text for ROI analysis results). (Y axis: Selectivity Index )

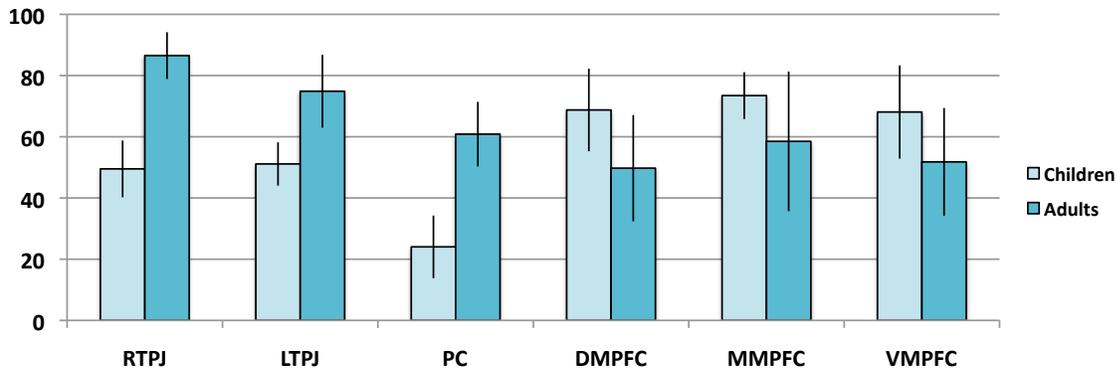
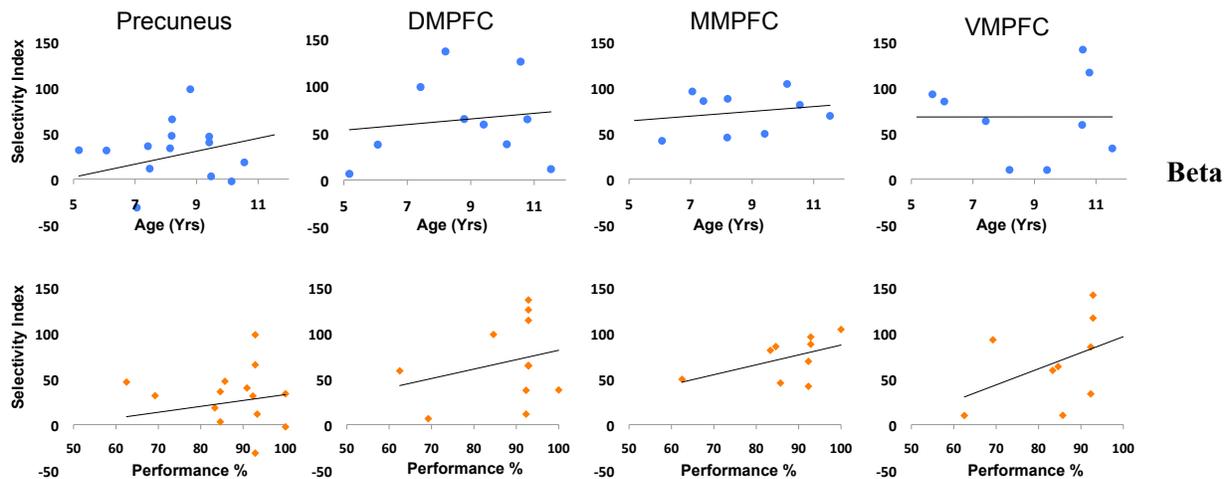


Figure S2.

Correlation between selectivity & age (top row), and selectivity & performance (bottom row) in PC, DMPFC, MMPFC, and VMPFC.



### coefficients

For ROI analysis, we report average percent signal change (PSC) in each condition relative to baseline (fixation) for individual ROIs, and calculated selectivity using these PSC values. However, we also conducted the same analysis using average beta coefficient (beta weights) instead of PSC for data acquired from children. Average beta weights for the Mental condition was significantly higher than average beta weights for the Physical condition, in all ROIs ((Mental) vs. (Physical); RTPJ: 1.45 vs. 0.25,  $t(15) = 7.53$ ; LTPJ: 1.28 vs. 0.16,  $t(12) = 9.01$ ; PC: 0.78 vs. -0.43,  $t(13) = 9.13$ ; DMPFC: 1.26 vs. 0.12,  $t(9) = 10.67$ , MMPFC: 1.07 vs. -.07,  $t(7) = 8.37$ ; VMPFC: 1.65 vs. 0.31,  $t(8) = 5.71$ . All comparisons  $p < 0.001$ ). We also calculated selectivity using beta weights:  $(100 * (\text{Mental} - \text{Social}) / (\text{Mental} - \text{Physical}))$ .

As expected, selectivity index calculated from PSC and beta weights were correlated in the RTPJ ( $N = 16$ ,  $r = 0.61$ ,  $p < 0.01$ ), LTPJ ( $N = 13$ ,  $r = 0.84$ ,  $p < 0.001$ ) and PC ( $N = 14$ ,  $r = 0.68$ ,  $p = 0.01$ ). Consistent with PSC results, we found a significant correlation between beta selectivity in the RTPJ and age, even after controlling for number of runs ( $N=16$ ,  $r(13) = 0.64$ ,  $p < 0.05$ ). Our critical finding, relationship between selectivity in the RTPJ and behavioral performance in ToM booklets (controlling for age and run numbers), was also significant with beta coefficients ( $N = 16$ ,  $r(13) = 0.57$ ,  $p < 0.05$ ).

### **Pilot study with fMRI story stimuli**

In the current study we have found that selectivity to mental state information in key brain regions – bilateral TPJ and PC – increases with age. However, there is an alternative explanation for these results that the observed neural change simply reflects a change in children’s pragmatics. Between ages 5 years and adulthood, there might be a change in the way they understand the stories. For example, younger children might be more likely to spontaneously consider the thoughts and desires of the characters even when these mental states are not explicit in the stories, which would result in heightened activation in brain areas selective to mental states during the Social condition. On the other hand, older children might be more likely to focus on the explicit content of the story, being more conservative in invoking mental states while listening to the stories. These cognitive differences would appear as neural differences in the fMRI results, but would not provide evidence for true developmental differences in the maturation or processing of specific brain systems.

In the current pilot study, we sought to provide evidence against this pragmatic interpretation that the developmental change in selectivity is due to changes in how children construe the stories by having a measure of how children construe our stories in the Mental, Social, and Physical conditions. To this end, we asked a separate group of children to listen to these stories and ‘tell the story back’ to the experimenter. Their responses would serve as a proxy for how children attend, remember and interpret our stimuli in the scanner.

### ***Methods***

Forty-five typically developing children (24 females; M age = 8.0 years; range: 5.1 – 11.7 years) were recruited from a local children’s museum to participate in this pilot task. All of the children were native speakers of English, and none of these children participated in the behavioral/fMRI session of the current study. Eight English stories in each of the three conditions (Mental, Social, Physical, 24 total) were divided into four playlists (2 stories from each condition, 6 stories in each playlist). The children were brought into a quiet room, and were presented with one or two playlists via headphones (the order of playlists was randomized across subjects). After listening to each story, the children were asked to tell the

story back to the experimenter. Children's responses were voice-recorded and then transcribed. We coded the total number of words in children's responses, number of mental state verbs (i.e., know, think), and the number of nouns and pronouns referring to a person. We also listed all the facts of any kind that were described in the stories (mean: 10.96 facts per story) and coded whether each of these facts was mentioned in children's responses.

### ***Results & Discussion***

We fit a linear mixed-effects model to the total number of words with age and conditions as fixed factors and subjects and stories as random factors (Bates & Sarkar, 2008; Gelman & Hill, 2007) with  $p$ -values set by posterior simulation. Older children produced longer answers (coefficient: 4.24,  $p < 0.0001$ ), but there was no difference in the length of children's answers, between the three story conditions ( $p = ns$ ). To analyze how many total facts were remembered, we fit a logit mixed-effects model with the same factors: again, older children remembered more facts over all ( $t =$  coefficient: 3.12,  $p < 0.0001$ ). In addition, children remembered marginally more facts in the Mental and Social conditions than in the Physical condition (coefficient: -3.90,  $p = 0.05$ ). To analyze the number of mental states and person/agent nouns in children's responses, we used a bias-reduced general linear model (Kosmidis, 2007) due to underdispersion in the data. We took a binary variable of whether each participant reported mental state verbs or person/agent noun in each condition, and ran a regression over these binary data. On these measures, there was no effect of age: younger children produced just as many mental state verbs, and agent nouns, as older children (mental state verbs: coefficient 0.15,  $p = ns$ ; agent nouns: coefficient 0.27,  $p = ns$ ). As predicted, children produced mental state verbs when recounting stories in the Mental condition, but not in the Social and Physical condition (Social: coefficient -4.04,  $p < 0.0001$ ; Physical: coefficient -6.58,  $p < 0.0001$ ), and they produced person/agent nouns or pronouns when they recounted stories in the Mental and Social conditions, but not in the Physical condition (Social: coefficient -0.004,  $p = ns$ ; Physical: coefficient -4.35,  $p < 0.0001$ ). These results provide support for our hypothesis that independent of age, children faithfully represent and retain the actual content of the story texts, and only rarely invent new entities, people or mental states that were not explicitly provided. That is, children of all ages described characters' thoughts and feelings only for stories in the Mental, not the Social, condition. Thus, there is no evidence that young children construe the stories differently, or are more likely to spontaneously consider the thoughts and feelings of characters in the Social stories.

### **References**

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Kosmidis, I. (2007). brglm: Bias reduction in binary-response GLMs, from <http://go.warwick.ac.uk/kosmidis/software>