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Intelligence and Neurophysiological Markers of Error Monitoring Relate to Children's Intellectual Humility

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This study explored developmental and individual differences in intellectual humility (IH) among 127 children ages 6–8. IH was operationalized as children's assessment of their knowledge and willingness to delegate scientific questions to experts. Children completed measures of IH, theory of mind, motivational framework, and intelligence, and neurophysiological measures indexing early (error-related negativity [ERN]) and later (error positivity [Pe]) error-monitoring processes related to cognitive control. Children's knowledge self-assessment correlated with question delegation, and older children showed greater IH than younger children. Greater IH was associated with higher intelligence but not with social cognition or motivational framework. ERN related to self-assessment, whereas Pe related to question delegation. Thus, children show separable epistemic and social components of IH that may differentially contribute to metacognition and learning.

In a world that provides constant opportunities to acquire new information, it is critical to have an awareness of the boundaries of your knowledge and understanding. Feeling confident about what you already know while remaining aware of what you do not know can be considered a hallmark of intellectual humility (IH; Samuelson, Church, Jarvinen, & Paulus, 2013). An accurate representation of your knowledge can guide decisions about when to solve a problem yourself and when to defer to a more knowledgeable individual. Although the concept of IH has been discussed among philosophers, research on the construct is in its early stages. Recent studies show that IH varies among individuals (Krumrei-Mancuso & Rouse, 2016; Meagher, Leman, Bias, Latendresse, & Rowatt, 2015) and that the folk construal of IH encompasses both epistemic and social dimensions (Samuelson et al., 2015). The epistemic dimension of IH includes being knowledgable and acknowledging the limitations of one's knowledge, whereas the social dimension involves accurately representing one's knowledge to other people and being open to their input.

Little is known about how behaviors reflecting the epistemic and social dimensions of IH emerge, how they interact with each other, and what factors contribute to their development. Here, we examine the relation between two behavioral markers that correspond to the epistemic and social elements of IH, respectively: knowledge self-assessment and willingness to defer to experts when answering a question. We also explore cognitive and neural factors that may contribute to individual and developmental differences in children's expression of the epistemic and social dimensions of IH.

The Epistemic Dimension: Knowledge Self-Assessment

Accurately evaluating one's own knowledge can be challenging. Adults often exhibit overconfidence in their knowledge and understanding (Dunning, 2011; Kruger & Dunning, 1999; Rozenblit & Keil, 2002), and young children are notorious for overestimating their knowledge and abilities across domains (e.g., Plumert, 1995; Shin, Bjorklund, & Beck, 2007; Spinath & Spinath, 2005). For example, when asked to estimate their understanding of familiar devices, 5-year-olds rate their knowledge more highly than 7- and 9-year-olds, despite actually knowing less

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(Mills & Keil, 2004). Developmental improvements in the accuracy of knowledge self-assessment may be related to improvements in memory, executive functioning, and social cognition, which are occurring during the early elementary school years (see Weisner, 1996). In particular, research on metacognitive development suggests that accurately judging one's own knowledge is closely tied to self-regulation and monitoring skills (see Schneider & Lockl, 2008 for a review). That said, prior research has focused on children's evaluations of how well they have learned new information (i.e., judgments of learning), and this information typically consisted of specific—and often arbitrary—facts (e.g., novel word pairs). In contrast, the current study focuses on children's judgments of their existing explanatory knowledge, which may be more challenging to evaluate, yet play an important role in learning (Keil, 2006).

Although children as young as age 3 overestimate their cognitive and physical abilities, there is a consistent developmental trend toward more accurate and realistic judgments as children enter elementary school (e.g., Lyons & Ghetti, 2011). Moreover, overconfidence levels vary among children of the same age (Destan & Roebers, 2015). This variability may be linked to the fact that individual differences in related capabilities, such as self-regulation, are also evident by preschool (Bronson, 2000). For example, in Shin et al.'s (2007) study, 22% of 6-year-olds and 14% of 7-year-olds did *not* initially overestimate their recall ability (and, in some cases, children even underestimated their recall). Likewise, although the majority of 5-year-olds in Mills and Keil's study (Experiment 1) rated themselves as highly capable of explaining how devices work, a few children rated their knowledge more conservatively (i.e., more similarly to their older counterparts; C. Mills, personal communication, July 28, 2016). These studies suggest that individual differences in knowledge self-assessment emerge by age 5. However, they did not explore what characteristics (other than age) relate to some children's ability to assess their knowledge more realistically than others. One possibility is that individual differences in overconfidence are not a direct function of the child's knowledge about the specific questions at hand but rather that they reflect different ways of monitoring and assessing performance (Efklides, 2011). The current study explores this possibility by measuring the relation between knowledge self-assessment and children's motivational framework, as well as children's neurophysiological responses to errors.

The Social Dimension: Question Delegation

What are the consequences of an excessively optimistic view of one's knowledge or abilities? Some researchers have argued that holding an overly optimistic view of themselves gives children a feeling of confidence or self-efficacy that motivates them to try new tasks and has positive effects on their actual performance (see Bjorklund, 2007). Conversely, in situations involving knowledge acquisition rather than task performance, overconfidence may pose an obstacle in that children who overestimate their knowledge and understanding of a topic may be less motivated to seek out assistance or learn new information about that topic (see Keil, 2006). If this is the case, children in the early elementary school years behave in ways that are seemingly at odds with each other: They are relatively poor judges of their own knowledge, yet they are quite good at seeking out information and reasoning about the distribution of knowledge in other minds.

By age 6, children have a basic understanding of the division of cognitive labor, and they can draw accurate inferences about the scope of another person's expertise even when the topic of expertise is unfamiliar (Lutz & Keil, 2002). Six-year-olds also understand that acquiring knowledge requires an intention to learn and attention to information (Sobel, Li, & Corriveau, 2007), and even an extremely knowledgeable person is incapable of answering questions in every domain (Danovitch & Keil, 2007). Research on self-regulated learning suggests that, among both children and adults, awareness of one's cognitive limitations, such as limitations on memory capacity, contributes to more successful learning strategies (Efklides, 2012). However, there is limited evidence about how children link judgments of their own knowledge to their decisions to seek out others' expertise. In a study by Aguiar, Stoess, and Taylor (2012), 4- to 6-year-old children chose whether to answer easy or difficult questions on their own, or to allow an expert to answer them instead. Children largely tried to answer the questions on their own, regardless of difficulty, although 6-year-olds deferred to the experts more often for difficult questions than for easy questions. These findings suggest that children's understanding of the limitations of their own knowledge may be linked to their decisions about when to consult others and that these two behaviors may be related to common underlying factors—a possibility explored in the current study. Aguiar, Stoess, and Taylor's data also suggest individual differences in children's willingness to delegate questions to experts. On average, 5-year-olds assigned questions to experts on approximately 12 of the 18 trials, yet four participants (18% of the sample) assigned questions to experts on all 18 trials and one child did not do so on any trial. This suggests that even at age 5, some children show more or less motivation to delegate questions to experts than their same-age peers.

Potential Contributors to IH

The research to date suggests that between ages 5 and 8 children grow better at accurately assessing their own knowledge, and they become more willing to defer to experts when answering difficult questions—behaviors that represent the epistemic and social dimensions of IH. The current study explores four factors that may contribute to developmental and individual differences manifesting the epistemic and social dimensions of IH: intelligence, theory of mind, motivational framework, and neural markers of error monitoring and control.

First, adults who are less knowledgeable are also less likely to be aware of or acknowledge their ignorance (i.e., the Dunning–Kruger effect; see Dunning, 2011). This phenomenon has been demonstrated across many domains and contexts, ranging from performance on examinations to making social judgments. With respect to rating one's explanatory knowledge, Rozenblit and Keil (2002) presented preliminary evidence of an inverse relation between intelligence (reflected by average scholastic aptitude test (SAT) scores at different universities) and knowledge ratings among college students. However, they did not directly measure intelligence. Spinath and Spinath (2005) reported a positive association between self-ratings of academic abilities and intelligence among third and fourth graders, a finding they explain in terms of the fact that intelligence predicts actual academic performance, which children become better at gauging at that age. In contrast, they reported no link between self-ratings and intelligence among first and second graders (and even a nonsignificant −.26 correlation among first graders). Thus, there may be developmental changes in the association between intelligence and IH. Similarly, intelligence predicts skepticism among 6- to 10-year-olds (Mills & Elashi, 2014), suggesting a relation between children's willingness to accept information they receive from others and their own knowledge, such that more intelligent children also think more critically about what they and other people know. Based on this evidence, we predicted that the 6- to 8-year-olds in our sample would show a positive relation between intelligence and both dimensions of IH, such that more intelligent children would be less likely to overestimate their understanding and more likely to delegate questions to experts.

The second factor of interest is children's ability to think about others' knowledge. Taking another person's perspective helps adults overcome biases (Galinsky & Ku, 2004; Galinsky & Moskowitz, 2000). Considering another person's point of view may be similarly valuable for children's developing ability to grasp that individuals—including themselves—can sometimes hold incorrect beliefs. Between ages 5 and 7, children solidify their understanding that other people can believe something to be true that they know to be false (Wellman & Liu, 2004), and they begin to realize that different people can interpret the same experience differently (i.e., interpretive theory of mind; Carpendale & Chandler, 1996). In addition, young children's mastery of theory of mind predicts their ability to determine who to trust (Fusaro & Harris, 2008), both components of evaluating and using information sources. Thus, we hypothesized that children who showed better performance on measures of theory of mind would have a better understanding of the limitations of their own knowledge and be more likely to seek out information from an expert.

The third factor we consider is children's motivational framework about intelligence. By the time they enter elementary school, children have already adopted incremental or entity theories of intelligence (Dweck, 1999; Gunderson, Gripshover, Romero, & Dweck, 2013). Children who hold an entity theory view intelligence largely as a fixed and unchangeable trait, and they emphasize performance outcomes over the process of learning. Conversely, children with an incremental theory view intelligence as malleable, and value opportunities for learning over opportunities to demonstrate their own intelligence (Dweck, 1999). We hypothesized that children who hold an incremental theory of intelligence would be more likely than children who hold an entity theory to acknowledge the limitations of their own understanding, as doing so would be less threatening to their view of their own intelligence. We also predicted that children who hold an incremental theory would be more likely to defer to an expert rather than trying to answer a difficult question on their own, because they would view the expert's input as an opportunity for learning.

The fourth factor we consider is children's ability to detect errors and react to them in adaptive ways

—that is, error monitoring. Our hypothesis was that basic error-monitoring functions relate to children's ability to monitor their knowledge and willingness to seek out and accept alternative views. Prior studies have examined how children's explicit metacognitive judgments relate to their learning strategies (e.g., Metcalfe & Finn, 2013), but ours is the first to investigate how children's online error-monitoring and detection processes may impact the judgments that contribute to self-regulated learning strategies. Behavioral and neural research suggests that when an error occurs two partly dissociable processes engage: (a) an immediate correction of the error and (b) later explicit detection and signaling of the error. Error correction appears to be automatic and can occur outside of awareness, whereas error detection is a slower more reflective process that gives rise to metacognitive awareness of and confidence in performance (Yeung & Summerfield, 2012). Our study illuminates the roles of these two mechanisms in IH by using the error-related negativity (ERN) and error positivity (Pe) as neural markers of error correction and error detection, respectively.

The ERN is an event-related brain potential (ERP) observed as a negative voltage change at scalp electrodes over the frontal cortex approximately 50 ms after making an erroneous response (Gehring, Goss, Coles, Meyer, & Donchin, 1993). The anterior cingulate cortex (ACC), a brain region involved in monitoring behavior and signaling the need for increased cognitive control, is the likely generator of the ERN (e.g., Gehring, Liu, Orr, & Carp, 2012). Additional sources of the ERN include a distributed network involving the prefrontal cortex and supplementary motor areas (Gehring et al., 2012). The Pe is a broad positive wave following the ERN that peaks at scalp locations over central and parietal cortex between 200 and 400 ms after an error is made (Ridderinkhof, Ramautar, & Wijnen, 2009). The Pe has several sources, including the ACC (van Veen & Carter, 2002), parietal cortex (Herrmann, Rommler, Ehlis, Heidrich, & Fallgatter, 2004), and insular cortex, which is involved in consciousness and awareness of body states (Ullsperger, Harsay, Wessel, & Ridderinkhof, 2010). Current conceptualizations suggest that the ERN and the Pe are dissociable neural signals involved in error monitoring, with the former reflecting error correction and the latter reflecting error detection and decision confidence (Hughes & Yeung, 2011). Both are thought to be involved in cognitive control and optimizing performance, but the Pe is more consistently related to observable adaptive behavioral adjustments following mistakes such as slower and more accurate responding, consistent with its role in explicit error detection and decision confidence (e.g., Moser, Schroder, Heeter, Moran, & Lee, 2011; Yeung & Summerfield, 2012).

There is a general consensus that the ERN increases with age in childhood (e.g., Davies, Segalowitz, & Gavin, 2004), consistent with the later maturation of the ACC (e.g., Mathalon, Whitfield, & Ford, 2003), and increases in behavioral indices of cognitive control (Donnellan, Conger, & Burzette, 2007). One recent review indicated the ERN and Pe are not yet fully mature even in late adolescence (Ferdinand & Kray, 2014). Despite this increase in ERN across development, a robust ERN can be elicited in young children as early as around 3 years of age (e.g., Grammer, Carrasco, Gehring, & Morrison, 2014). Although less consistent, the Pe also increases over time and can be elicited in children 3 years and older (Grammer et al., 2014; Lo, Schroder, Moran, Durbin, & Moser, 2015; Torpey, Hajcak, Kim, Kujawa, & Klein, 2012). These findings indicate the ERN and Pe are intact for our current study, which focused on children between ages 6 and 8. They also suggest that like awareness of the boundaries of one's knowledge and the tendency to seek out advice from others, the ERN and Pe are actively undergoing development during the early elementary school years.

Preconscious error correction, as indexed by the ERN, may serve as a precursor to error detection and awareness (Hughes & Yeung, 2011). Just as awareness of one's knowledge may predict question delegation, error correction may provide initial information about one's performance that is used to determine whether errors have occurred and changes need to ensue. Therefore, we propose that enhanced ERN may show associations with greater IH insomuch as it serves to initiate a cascade of remedial actions. Because the Pe is characterized as a deeper, more reflective process related to error detection and decision confidence, and it is related to learning behaviors such as adaptive adjustments after mistakes, we predicted that larger Pe amplitudes may relate to more realistic estimations of knowledge and increased willingness to delegate questions to experts (i.e., greater IH).

Design of Current Study

Our study focused on children ages 6 through 8 years as this is a period in development when children become more realistic in assessing their knowledge and understanding (Mills & Keil, 2004), and may become more willing to delegate questions to experts (Aguiar et al., 2012). At these ages, children also exhibit improvements in theory of mind, executive function, memory, and other skills that may relate to IH (Weisner, 1996). In addition, children ages 6 through 8 show robust ERN and Pe signals.

In our analyses, we first examined each dimension of children's IH and investigated the relation between them. We then examined the relative contribution of age and individual differences in motivational framework, theory of mind, intelligence, and error-monitoring ERP components to each dimension of IH using hierarchical regression.

Method

Participants

Participants were 127 children (63 female) ages 6 through 8 (M = 7.10, range = 6.02–8.27 years) from the Lansing, Michigan region who met eligibility criteria (see Supporting Information). According to parent reports, 87% of children were non-Hispanic and 9% were Hispanic (parents of the other 4% chose not to respond). Approximately 84% of the children were Caucasian American, 3% were Asian American, 2% were African American, 9% were identified as belonging to two or more ethnic groups, and 1% were identified as belonging to an ethnic group not listed on the demographic questionnaire (1% chose not to respond). Data were collected from June 2013 to July 2014.

Procedure

Children were interviewed individually by the same female experimenter. All tasks, except for the ERP measures, were presented in a fixed order in a session lasting approximately 60 min. The fixed order of tasks was as follows: motivational framework, knowledge rating, false belief, ambiguous figure, Kaufman Brief Intelligence Test, 2nd ed. (KBIT–II), question delegation, hidden emotions, sarcasm, ambiguous referential communication, and belief revision. (The belief revision task is beyond the scope of the current article and will not be discussed further.) In order to maintain children's interest and motivation, children received small prizes after completing the knowledge rating, KBIT–II, and ambiguous referential communication tasks. After completing the entire set of tasks, children were outfitted with the electroencephalogram (EEG) cap and completed the ERP measures—a process that lasted 60–90 min.

IH Measures

Knowledge Rating

The self-assessment of explanatory knowledge was adapted from Mills and Keil (2004). Children were trained to use a 5-point star scale to rate their knowledge (see Supporting Information for procedure). Following the training and practice items, children used the star scale to rate their knowledge of 12 items presented in the format of "Think about how much you know about ______. How many stars would you give for what you'd say about _______?" The items included six biological items (e.g., why fish can only live in water, why some people are born with red hair) and six mechanical items (e.g., how an elevator works, why cars need gas to work; see Supporting Information). All items were drawn from Lutz and Keil's (2002) study, (Experiment 1), with two items in each domain tapping into the stereotypical roles, normal functioning, and underlying principles associated with a doctor's or a mechanic's expertise. Items were presented in one of two pseudorandom orders, with no more than two consecutive items from each domain. Higher scores reflected more positive ratings of one's knowledge.

Question Delegation

The question delegation task was modeled closely on Lutz and Keil (2002) and Aguiar et al. (2012). Children were told that they would be playing a game with two teammates, a doctor and a mechanic, and were provided with a description of each person's expertise. Each teammate was represented by a photograph of a man wearing stereotypical doctor or mechanic attire. Children were instructed that the goal of the game was to see how many questions their team could answer correctly and that they would receive one point for each correct answer. However, first, children would decide who would answer each question. Children were instructed to keep some questions for themselves to answer but were told that if they did not know the right answer, they could ask one of their teammates to answer it and they should choose the teammate who would get it right. Items were presented in the following format: "The question is ____. Who will answer that question? The mechanic, the doctor, or you?" The question statements were the same as in the knowledge rating task, presented in the same order. The order in which the mechanic or doctor were presented was also balanced across subjects.

Theory of Mind

Children completed the standard false belief task, the hidden emotion task, and the sarcasm task (Peterson, Wellman, & Slaughter, 2012; Wellman & Liu, 2004), in addition to the ambiguous figure task and the ambiguous referential communication task (Carpendale & Chandler, 1996). These tasks were selected based on evidence that they tap into a developmental progression between ages 6 and 8. Scores for all tasks combined ranged from 0 to 7 (see Supporting Information for administration and scoring details).

Motivational Framework About Intelligence

Children completed eight items from the measure of motivational framework about intelligence used by Gunderson et al. (2013) where they indicated agreement with statements on a 1–5 scale (see Supporting Information for details).

Intelligence

Children's verbal and nonverbal intelligence were measured using the KBIT–II (Kaufman & Kaufman, 2004).

Error-Monitoring Task

Following the behavioral tasks, children were fitted with the EEG cap and seated approximately 60 cm in front of a computer monitor. The task was a picture version of the Go/No-Go task developed by Rueda, Posner, Rothbart, and Davis-Stober (2004) that has been used with other samples of young children to investigate the ERN and Pe (Grammer et al., 2014; Lo et al., 2015) and followed Grammer et al.'s procedures. Children were asked to help a zookeeper capture animals that had escaped from their cages by pressing the spacebar when they viewed the target animal (Go stimuli). They were presented with images of three orangutans that were helping the zookeeper and therefore did not need to be put back in their cages; children were instructed to withhold pressing the spacebar when they saw one of these orangutans (No-Go stimuli). Children were instructed to respond as quickly and accurately as possible. During each trial, a color photo of a zoo animal was presented at a central location on the computer monitor. Each stimulus was presented for 750 ms and the intertrial interval was 500 ms. After completing practice blocks to ensure adequate responding, participants completed eight blocks of 40 trials (30 Go trials and 10 No-Go trials). Participants received feedback at the end of each block. Faster performance was encouraged if accuracy was above 90%, and more accurate performance was encouraged if accuracy fell below 60%. Otherwise, children were told: "You're doing a great job!" A visual representation of this task is available in Grammer et al. (2014).

Psychophysiological Recording and Data Reduction

Continuous EEG activity was recorded from 64 Ag-AgCl electrodes placed in accordance with the 10/20 system using the ActiveTwo BioSemi system (BioSemi, Amsterdam, The Netherlands). In addition, two electrodes were placed on the left and right mastoids. Electrooculogram activity generated by eye movements and blinks was recorded at FP1 and three additional electrodes placed inferior to the left pupil and on the left and right outer canthi. During data acquisition, the Common Mode Sense active electrode and Driven Right Leg passive electrode formed the reference and ground, as per BioSemi's design specifications. All signals were digitized at 1024 Hz using ActiView software (BioSemi). Offline analyses were performed using BrainVision Analyzer 2 (BrainProducts, Gilching, Germany). Scalp electrode recordings were re-referenced to the numeric mean of the mastoids and bandpass filtered with cutoffs of 0.1 and 30 Hz (12 dB/oct roll-off). Ocular artifacts were corrected using the method developed by Gratton, Coles, and Donchin (1983). Physiologic artifacts were detected by a computer-based algorithm such that trials in which the following criteria were met were rejected: a voltage step exceeding 50 μV between contiguous sampling points, a voltage difference of more than 200 μV within a trial, or a maximum voltage difference less than 0.5 μV within a trial. After data reduction, 124 children were retained for ERP analysis ($n = 3$ lost due to unusable EEG data based on artifact detection).

ERP data were segmented starting 500 ms prior to the response and an additional 800 ms postresponse. Consistent with previous developmental studies (e.g., Kessel et al., 2016; Meyer, Riesel, & Proudfit, 2013), we analyzed ERPs at the electrode sites where the component was maximal. The ERN was analyzed at FCz, and the Pe was analyzed at Pz, where these ERPs were maximal. The ERN and its correct-trial counterpart (correct-response negativity [CRN]) were quantified as the average voltage in the 0–100 ms postresponse time window. The Pe on error and correct trials was quantified as the average amplitude in the 200–400 ms postresponse window. ERPs were calculated relative to a 200-ms pre-response window baseline correction. For the ERN at FCz, there was an average of 27.54 trials (SD = 9.35, range = 10–52), and for the CRN at FCz, there was an average of 209.82 trials (SD = 22.91, range = 117–239). For the Pe at Pz, there was an average of 27.49 trials (SD = 9.66, range = 7–52), and for the Pe-correct (Pe-C), there was an average of 207.67 trials (SD = 29.33, range = 62–239).

All analyses were conducted using SPSS version 21 software (IBM, Armonk, NY, USA). Greenhouse-Geisser corrected p values were applied as appropriate for repeated measures analysis of variance (ANOVA) models.

Results

Mean scores, standard deviations, and ranges for motivational framework, verbal and nonverbal IQ, theory of mind, knowledge rating, question delegation, and ERPs are listed in Table 1.

IH Measures

Knowledge Rating

Across all of the items, children's mean scores ranged from 1.33 to 4.67 (M = 3.05, SD = 0.72) and the scores had an approximately normal distribution. We calculated mean ratings for each of the items by category (biological or mechanical). Preliminary analyses suggested no effects of question order, so this variable was excluded from further analyses. A 2 (item category) × 2 (gender) repeated measures ANOVA showed a main effect of item category, $F(1, 125) = 7.940$, $p = .006$, $\eta_p^2 = .060$, but not of gender. Children gave lower ratings for their knowledge of mechanical items (M = 2.93, SD = 0.84) than biological items (M = 3.18, SD = 0.79), $t(126) = 2.772$, $p = .006$, $d = 0.307$.

Question Delegation

Children assigned more of the questions to an expert (M = 8.76 of the 12, SD = 1.79) than to themselves (M = 3.24 of the 12, SD = 1.79), and no child chose to assign the question to themselves on more than eight trials (range = 0–8). In the 1,113 trials where children chose an expert to answer the question, they selected the correct expert on 1,095 trials (98.4%); thus, choice of expert was not considered in the analyses.

Preliminary analyses showed no effect of the order in which the mechanic or doctor were presented; thus, this variable was excluded from further analyses. A 2 (item category: biological or mechanical) × 2 (gender) × 2 (question order: biological item or mechanical item first) repeated measures ANOVA showed a significant main effect of item category on the number of times in which children chose to assign the question to themselves, $F(1, 123) = 71.598$, $p < .001$, $\eta_p^2 = .368$, but no main effects of gender or question order. The main effect of item category was embedded in a significant interaction between item category and question order, $F(1, 123) = 35.109$, $p < .001$, $\eta_p^2 = .222$. Children who heard a biological item first were significantly more likely to defer to an expert on the biological questions (M = 1.64 questions assigned to themselves, SD = 1.02) than children who heard a mechanical item first (M = 2.58, SD = 1.24), $t(125) = 4.68$, $p < .001$, $d = .828$. Similarly, children who heard a mechanical item first were more likely to defer to an expert (M = 0.92, SD = 1.06) on mechanical questions than children who heard a biological item first (M = 1.36, SD = 1.05), $t(125) = 2.347$, $p = .020$, $d = 0.417$.

Relation Between IH Measures

Controlling for age, we found a significant correlation between knowledge rating and question delegation, $r(124) = .180$, $p = .044$, without controlling for age, $r(124) = .163$, $p = .067$. Children who rated themselves as knowing more about the questions tended to assign more questions to themselves than to the experts, and children who rated themselves as knowing less tended to delegate questions to the experts more often. This suggests that our IH measures tapped into related, although not identical, judgments.

Error-Monitoring Results

Analysis of behavioral and EEG data were conducted on the 124 children with complete data for all measures.

Behavioral Results

On average, children committed 32.44 (SD = 10.46) false alarms on No-Go trials and 235.43 (SD = 5.14)

Table 1
Correlations and Partial Correlations (Controlling for Age) for Primary Behavioral (n = *127) and ERP* (n = *124) Measures*

	Descriptive statistics									
	M	*SD*	Range	1	2	3	4	5	6	7
1. Age	7.10	0.64	6.02 to 8.26	—	—	—	—	—	—	—
2. Motivational framework	3.48	0.88	1.5 to 5	.25**	—	—	—	—	—	—
3. Verbal IQ	113.54	11.97	89 to 146	.06	.24* (.23*)	—	—	—	—	—
4. Nonverbal IQ	105.93	15.26	75 to 140	.14	.20* (.17)	.41** (.41**)	—	—	—	—
5. Theory of mind	3.65	1.48	0 to 7	.33**	.24* (.18*)	.39** (.39**)	.23* (.19*)	—	—	—
6. IH: knowledge rating	3.05	0.72	1.3 to 4.7	−.18*	−.09 (−.04)	−.28* (−.27*)	−.29** (−.27**)	−.14 (−.09)	—	—
7. IH: question delegation	3.24	1.88	0 to 8	.08	.17 (.15)	.053 (.05)	.02 (.01)	.07 (.05)	.16 (0.18*)	
8. ERN	−3.39	4.79	−14.68 to 9.31	−.16	—[a]	.18* (.19*)	−.04 (−.02)	.02 (.07)	−.08 (−.11)	−.02 (.00)
9. CRN	4.55	3.53	−4.15 to 14.03	−.07	—	.07 (.07)	−.06 (−.05)	.03 (.05)	.13 (.12)	−.05 (−.04)
10. ΔERN	−7.94	4.54	−18.80 to 2.29	−.11	—	.13 (.14)	.01 (.02)	.00 (.03)	−.19* (−.21*)	.01 (.02)
11. Pe	5.21	5.61	−14.17 to 17.03	.05	—	.10 (.10)	.09 (.09)	−.06 (−.08)	−.10 (−.09)	−.20* (−.20*)
12. Pe-C	−2.94	4.73	−14.60 to 9.07	−.12	—	.07 (.08)	.00 (.02)	−.07 (−.03)	.03 (.01)	−.16 (−.15)
13. ΔPe	8.16	5.45	−4.06 to 24.38	.15	—	.04 (.03)	.09 (.07)	.00 (−.05)	−.13 (−.11)	−.07 (−.08)

Note. ERN = error-related negativity; CRN = correct-response negativity; ΔERN = ERN − CRN; Pe = error positivity; Pe-C = Pe-correct; ΔPe = Pe − Pe-C; ERPs = event-related brain potential; IH = intellectual humility.
[a]Correlations between ERPs and motivational framework reported in previously published article (Schroder et al., 2017).
*$p \leq .05$. **$p \leq .01$.

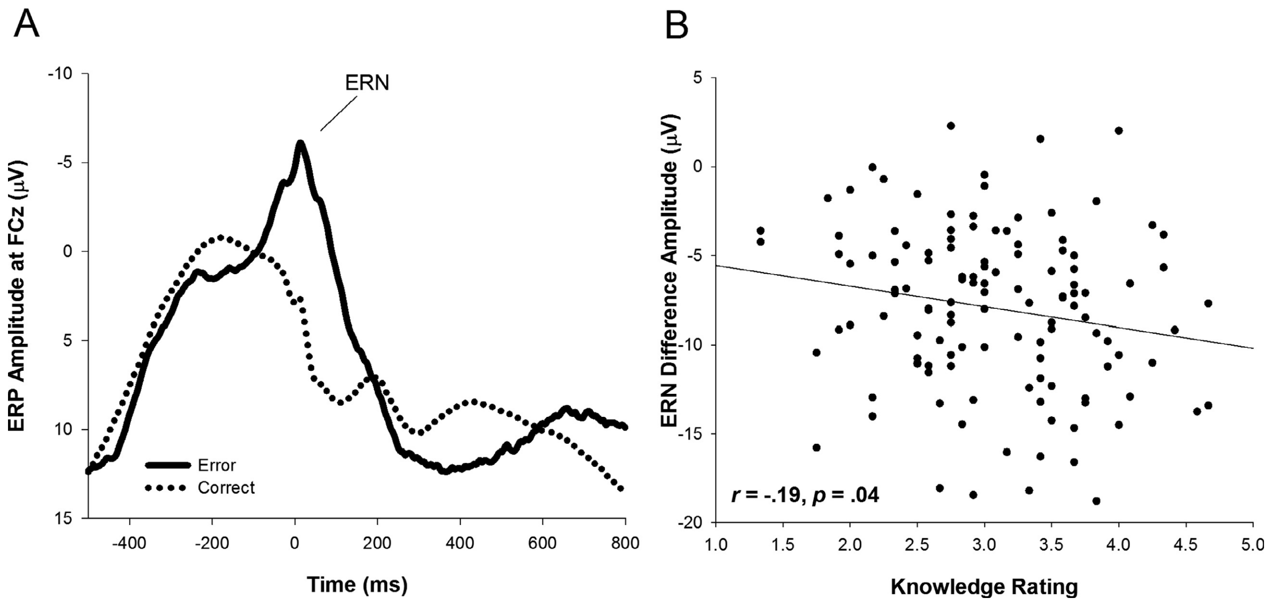

Figure 1. (A) Grand-averaged waveforms depicting error-related negativity (ERN) and correct-response negativity (CRN) waveforms at electrode FCz, where they were maximal. Note that negative is plotted up on the *y*-axis, as is convention for event-related brain potential (ERPs). (B) Scatter plot depicting relation between ERN difference wave (ERN − CRN) and knowledge ratings.

correct hits on Go trials. As is typical for the Go/No-Go paradigm, children were faster on false alarms (M = 417.69 ms, SD = 50.02) compared to correct hits (M = 510.50 ms, SD = 59.92), $t(123) = 25.96$, $p < .001$, $d = 1.68$. With regard to posterror adjustments, children exhibited the typical slowing on Go correct trials after No-Go errors/false alarms (M = 538.12, SD = 81.66) compared to after No-Go correct rejects (M = 520.80, SD = 68.17), $t(123) = 2.84$, $p = .005$, $d = 0.23$,—that is, posterror slowing. Posterror accuracy (M = 90.45, SD = 7.03) was slightly higher than postcorrect accuracy (M = 89.28, SD = 3.83), $t(122) = 1.77$, $p = .08$, $d = 0.17$.

EEG Results

We report analyses from a one-factor (accuracy: error vs. correct) repeated-measures ANOVA to establish basic error-monitoring effects.

Consistent with the presence of an ERN, there was a significant main effect of accuracy, $F(1, 123) = 379.14$, $p < .001$, $\eta_p^2 = .76$, indicating that negativity was larger on error trials (M = −3.38, SD = 4.79) compared to correct trials (M = 4.55, SD = 3.53; see Figure 1). Consistent with the presence of a Pe, there was a significant main effect of accuracy, $F(1, 123) = 415.78$, $p < .001$, $\eta_p^2 = .77$, and, as expected, amplitudes were more positive for error (M = 8.25, SD = 5.71), relative to correct (M = −2.32, SD = 4.86) trials.

We submitted the ERN, CRN, Pe, and Pe-C to correlational and regression analyses. To isolate error-related brain activity, we also submitted the difference between the ERN and CRN (i.e., ΔERN) and the difference between the Pe and Pe-C (i.e., ΔPe) to correlational and regression analyses.

Relations Between IH, Theory of Mind, Motivational Framework, Intelligence, and ERPs

Table 1 displays bivariate correlations between the variables. Higher knowledge ratings (lower IH) were related to younger age, lower verbal and nonverbal IQ, and larger ΔERN (Figure 1). Higher question delegation scores (higher IH) were related to larger Pe (Figure 2).

Prior to conducting the main analyses of interest that considered the extent to which our predictor variables accounted for individual differences in IH, we examined relations between the IH variables and behavioral performance from the error-monitoring task. This was important to determine whether behavioral performance should also be included in the main analyses.

Knowledge ratings were not reliably related to No-Go errors/false alarms ($r = -.16$, $p = .08$) nor was there a significant association between question delegation scores and No-Go error rate ($r = -.11$, $p = .21$). These relations remained unchanged after controlling for age. Higher knowledge ratings were

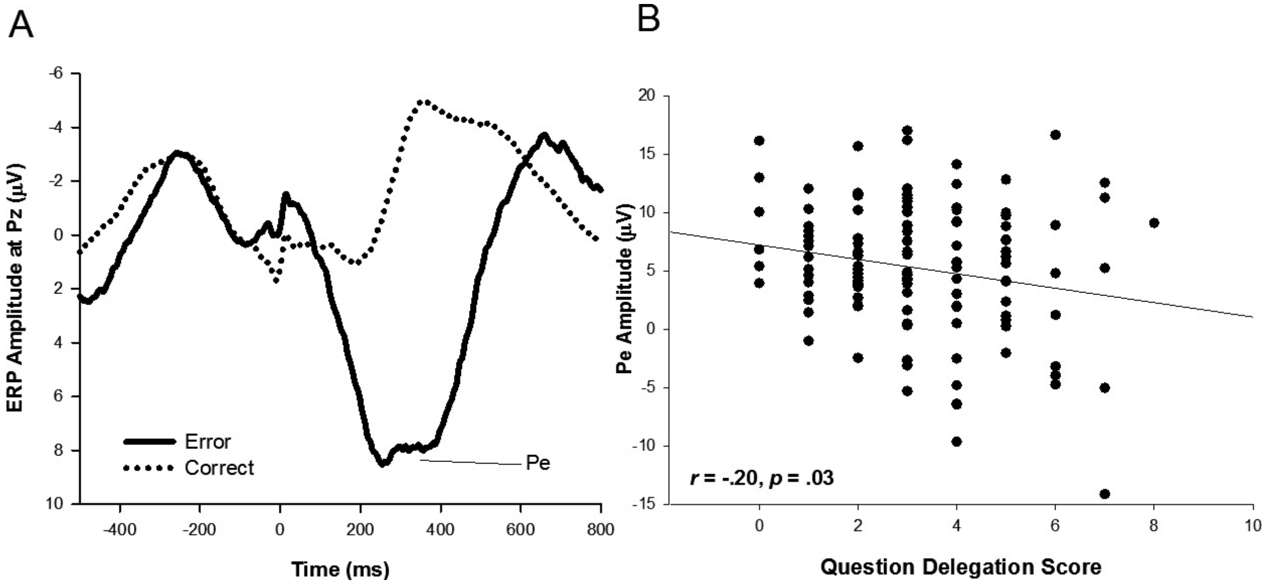

Figure 2. (A) Grand-averaged waveforms depicting error positivity (Pe) and Pe-correct waveforms at electrode Pz, where they were maximal. Note that negative is plotted up on the *y*-axis, as is convention for event-related brain potential (ERPs). (B) Scatter plot depicting relation between amplitude of the Pe waveform and question delegation score.

significantly correlated with slower reaction times (RTs) on Go correct hit trials ($r = .22$, $p = .01$), but not on No-Go errors/false alarms ($r = .04$, $p = .66$). After controlling for age, however, Go correct hit RT was no longer reliably associated with knowledge ratings ($r = .16$, $p = .08$). Question delegation ratings showed no significant association with reaction times (rs $< -.10$, ps $> .27$). Neither knowledge ratings nor question delegation scores were associated with posterror adjustments (rs $< |.08|$, ps $> .39$). Because none of the behavioral measures were significantly related to IH measures after controlling for age and were not the main focus of this investigation, we did not consider them further in the main regression analyses reported below.

A hierarchical regression analysis was conducted to examine the extent to which each of the five predictors accounted for individual differences in children's knowledge ratings, after controlling for age (see Table S1). Age was entered in the first block, explaining 3.1% of the variance in knowledge ratings. After entering the additional predictors, the amount of variance accounted for significantly increased to 14.3%, $F(6, 116) = 3.48$, $p = .005$. The only predictors that were significantly related to knowledge assessment were nonverbal IQ ($B = -.009$, $p = .043$) and ΔERN ($B = -.031$, $p = .028$). (The relation to verbal IQ was marginally significant, $B = -.011$, $p = .085$; and, if full scale IQ was used instead of the separate subscales, it remained significantly related to knowledge ratings in the regression, $B = -.017$, $p = .001$—see Table S2 for details.) Higher nonverbal IQ and smaller ΔERN were associated with lower knowledge self-assessment scores (i.e., greater IH). When hierarchical regression was used to examine the predictors of question delegation, age only accounted for .6% of the variance and the amount of variance did not significantly increase with the addition of the predictor variables (see Table S3). Nonetheless, Pe amplitude emerged as the sole significant predictor of question delegation scores ($B = -.068$, $p = .022$).

Discussion

This study investigated the relation between two dimensions of IH—knowledge self-assessment and willingness to consult experts—and potential cognitive and neurobehavioral predictors of these behaviors. Children ages 6 through 8 who rated their knowledge more conservatively were more likely to assign questions to an expert than to themselves. Children's knowledge ratings were predicted by IQ, such that children with higher IQ scores gave lower (i.e., more conservative) knowledge ratings than did children with lower IQ scores. However, IQ did not predict question delegation. There was also no relation between either measure of IH and children's theory of mind nor their motivational framework.

In addition, there were differential associations between each of the behavioral measures of IH and neurophysiological measures of error monitoring. After accounting for all associations together, smaller ERN remained independently related to lower knowledge ratings (reflecting greater IH). Larger Pe was related to more frequent delegation of questions to experts (also reflecting greater IH).

One of the primary objectives of this study was to examine how the epistemic and social dimensions of IH in children relate to each other. Responses to the two types of judgments reflecting IH were related but were far from perfectly aligned. This is surprising considering that the knowledge rating and question delegation tasks involved the same target questions and that children showed no difficulty assigning questions to the correct expert in the question delegation task, suggesting that they understood the items and were paying attention. Notably, children who rated themselves as highly knowledgeable about the questions in the knowledge rating task (reflecting lower IH in the epistemic dimension) still assigned questions to the experts on at least one third of the trials in the question delegation task that took place just a short while later. One potential explanation for the relatively weak link between tasks is that the knowledge rating task may have prompted children to prioritize appearing knowledgeable over being accurate, because children faced no repercussions for inaccurate judgments or inflated ratings. However, in the question delegation task, children may have prioritized accuracy over reputation management because they believed they would have to demonstrate their knowledge later and that their team would only gain points for correct answers. Similarly, children who gave themselves high ratings may have thought that even though they knew a great deal about the answer to the target question, an expert would still know more than them, and thus they chose the expert in the question delegation task.

The ERP data also suggest that the divergence in children's responses to the knowledge rating and question delegation tasks reflects differential associations between each dimension of IH and error-monitoring mechanisms. Contrary to our prediction, higher knowledge ratings (reflecting lower IH) were associated with enlarged ERN, specifically, the ΔERN. On the other hand, consistent with our expectation, higher question delegation scores (reflecting higher IH) were associated with larger Pe amplitude. These represented dissociable relations and point to interesting possible differences between components of IH.

The finding that higher knowledge ratings were related to larger ΔERN suggests greater initial error correction in children with lower IH. That children with higher knowledge ratings also demonstrated similar or somewhat slower performance suggests less efficient task performance relative to children with lower knowledge ratings (higher IH). That is, children with higher IH were more efficient in the Go-No/Go task, allocating fewer resources toward error correction and performing the task as, or more, quickly than children with lower IH (cf. Schroder & Moser, 2014). We speculate that children who rate their own knowledge highly are more likely to give incorrect answers to questions, and therefore they may have historically received and incorporated more feedback about making mistakes (e.g., encouragement to work more slowly and carefully to avoid mistakes). In contrast, children who are more aware of the limitations of their knowledge may be less likely to answer questions incorrectly, resulting in less corrective feedback and leading them to rely less on immediate error correction mechanisms. Future studies could explore this possibility by examining children's likelihood of incorrectly answering questions, their approach to mistakes, and the frequency of corrective feedback that parents and teachers provide.

Consistent with our expectations, higher question delegation scores were related to larger Pe. These data suggest that children with higher IH paid closer attention to their mistakes, or were more aware of having made a mistake. Recent work also suggests the Pe reflects the strength of accumulated evidence that an error occurred, thus representing an early error detection mechanism that is linked to conscious judgments of accuracy and subsequent behavioral adjustments (Steinhauser & Yeung, 2010). Steinhauser and Yeung showed that adopting a high evidence criterion for responding in a difficult discrimination task prompted a larger Pe. That this larger Pe tracked with the tendency to delegate questions in the current study raises the intriguing possibility that the question delegation task did indeed encourage children to aim for metacognitive accuracy rather than reputation management. Thus, children who delegated more questions set a higher criterion for responding on their own. This suggests that individual differences in neurophysiological responses to errors may explain why some children are more likely to seek out information from others, regardless of their prior knowledge self-assessment.

The finding that intelligence was predictive of knowledge ratings, but not question delegation, provides further evidence that, although the epistemic and social dimensions of IH are related, different underlying processes may contribute to each one. Together with prior studies showing an inverse relation between children's actual knowledge and their knowledge ratings (Mills & Keil, 2004), our findings suggest that children are susceptible to the Dunning–Kruger effect (Dunning, 2011), such that children who know less are also less aware of what they do not know and are more likely to overestimate their knowledge. In addition, the absence of an association between intelligence and question delegation scores in our study suggests that less intelligent children are not necessarily at a disadvantage compared to their more intelligent peers when it comes to using effective learning strategies. However, further research is needed to explore the mechanisms underlying children's decisions to delegate questions and how educators could potentially capitalize on children's overall willingness to seek out information.

One caveat in interpreting our findings is that our study involved questions about domains that were familiar to children but in which children were likely to have had limited formal education. Adults are more likely to overestimate their knowledge—or even to claim to know nonexistent facts—about familiar domains (Atir, Rosenzweig, & Dunning, 2015) and passive expertise gained through familiarity with a topic is more likely to result in illusions of understanding for adults with lower amounts of formal education about that topic (Fisher & Keil, 2015). Thus, children may show different response patterns if they are asked about nonscientific domains (see Kuhn, 2009) or less familiar topics. Just as other metacognitive abilities in children ages 5 through 8 depend on domain-specific content knowledge (Vo, Li, Kornell, Pouget, & Cantlon, 2014), children may show high IH in one domain but low IH in others.

Finally, the current study found no associations between children's theory of mind or motivational framework and IH. As in other recent work suggesting that theory of mind does not play a major role in judgments of expertise (Danovitch & Noles, 2014), the contribution of theory of mind to IH may be relatively minor. However, additional research is needed to examine the role that social cognition, more broadly, may play in IH. For example, it may be valuable to focus on children's understanding of mental states in general and not only their perspective taking skills (see Knutsen, Frye, & Sobel, 2014). Social cognitive skills could also be critical in situations where children find it more challenging to select the best expert or they have to assess the expert's trustworthiness (Fusaro & Harris, 2008; Mills & Elashi, 2014). Likewise, although motivational framework was unrelated to IH in the current study, such an effect may be measurable later in development as children's motivational frameworks become more influential on observable achievement outcomes (see Dweck, 2003). Moreover, there may be additional mediators and moderators between motivational framework and IH that we did not explore in this study, such as achievement goals and approach versus avoidance tendencies (see Burnette, O'Boyle, VanEpps, Pollack, & Finkel, 2013 for a meta-analysis).

Summary and Conclusions

The current results support the idea that there are separate epistemic and social components of IH and that they do not necessarily develop at similar rates (Samuelson et al., 2015). Our findings suggest that among children ages 6 through 8, the social component of IH may be more well developed or more apparent than the epistemic one. Further research with a wider age range is needed to confirm this pattern and to better understand whether it reflects practical considerations (e.g., wanting to increase the likelihood of a correct answer), changes in help-seeking behaviors (Marchand & Skinner, 2007), or broader improvements in metacognitive awareness (Schneider & Lockl, 2008). Our results also suggest that, like adults, children who know less (i.e., are less intelligent) are more likely to overestimate how much they know. However, awareness of their own knowledge only moderately relates to children's ability to make appropriate judgments about when to answer questions on their own or defer to experts. Thus, it may not be necessary for children to realize what they do not know in order to motivate them to engage in effective learning behaviors (e.g., asking questions, seeking out expertise). This finding suggests that when educating younger elementary school-age children, it may be more effective to emphasize teaching children how to find the answers to their questions than to invest energy in prompting them to realize the limitations of their own knowledge (e.g., through self-assessment). Future research should also explore how the relation between intelligence and IH influences learning behaviors in children with low IQ scores and atypically developing children. For example, children with attention deficit hyperactivity disorder who show a positive illusory bias, where their self-reported competence is much higher than their actual competence (see Owens, Goldfine, Evangelista, Hoza, & Kaiser, 2007), may still show relatively intact abilities to seek out information from others. If so, interventions could potentially leverage these intact abilities to support learning.

Moreover, that the neurophysiological markers of cognitive control related to error monitoring suggests that knowledge self-assessment and question delegation represent two separable components of IH. Children who showed greater IH in their knowledge ratings had lower ΔERN, whereas children who showed greater IH in question delegation had larger Pe. These differences in neurophysiological markers corresponding to the epistemic and social dimensions of IH can potentially help account for the variability in IH behaviors among individuals.

By combining behavioral and EEG measures, we aimed to more fully characterize the nature of IH as a biopsychological phenomenon. This *psychoneurometric* approach (Patrick, Durbin, & Moser, 2012) allows us to develop more comprehensive models of the IH construct as well as further refine measures across domains (i.e., discern whether certain measures are better or worse indicators of IH). Although correlations between behavioral measures of IH and EEG measures of error monitoring were small, this is to be expected because they are derived from such disparate domains—self-report on one task with ERPs from another—that have unique sources of method variance (Campbell & Fiske, 1959). This should not imply that the relations are unimportant, however. Rather, this study is the first of many, we hope, to begin developing a biopsychological conceptualization of IH. Measurement differences aside, building composite measures that index the construct of IH across domains of behavior, physiology, and experience will surely contribute to a further appreciation of IH and its utility in providing insights into the development of children's metacognitive judgments and learning.

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Supporting Information

Additional supporting information may be found in the online version of this article at the publisher's website:

Figure S1. Scatter Plot Showing Distribution of Theory-of-Mind Scores

Figure S2. Topographic Map of Error-Related Negativity (ERN; Left) and Error Positivity (Pe; Right) Time Windows Illustrating Scalp Distribution of Difference Wave (Error Minus Correct)

Table S1. Hierarchical Regression Results Predicting Knowledge Ratings (n = 124)

Table S2. Hierarchical Regression Results Predicting Knowledge Ratings (n = 124)

Table S3. Hierarchical Regression Results Predicting Question Delegation Score (n = 124)