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Knowing your heart and your mind: The relationships between metamemory and interoception

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ABSTRACT

Humans experience a unified self that integrates our mental lives and physical bodies, but many studies focus on isolated domains of self-knowledge. We tested the hypothesis that knowledge of one's mind and body are related by examining metamemory and interoception. We evaluated two dimensions of metamemory and interoception: subjective beliefs and the accuracy of those beliefs compared to objective criteria. We first demonstrated, in two studies, that metamemory beliefs were positively correlated with interoceptive beliefs, and this was not due to domain-general confidence. Finally, we showed that individuals with better metamemory accuracy also had better interoceptive accuracy. Taken together, these findings suggest a common mechanism subserving knowledge of our cognitive and bodily states.

1. Introduction

"Know thyself," says the ancient Greek maxim, not "Know thy thinking self" or "Know thy feeling self." However, studies of self-knowledge have, for the most part, been limited by domain. There are studies of how one knows thy thinking self (e.g., Fleming, Weil, Nagy, Dolan, & Rees, 2010; Kelemen, Frost, & Weaver, 2000) and studies of how one knows thy feeling self (e.g., Brackett, Rivers, Shiffman, Lerner, & Salovey, 2006; Robinson & Clore, 2002; Spain, Eaton, & Funder, 2000), but the current literature leaves open the question of whether and how these forms of self-knowledge are related (e.g., Fleming, Ryu, Golfinos, & Blackmon, 2014; Kelemen et al., 2000; Schraw, 1998; Song et al., 2011). That is, is the knowing when we recognize an acquaintance in a crowd, or that we've forgotten an item on the grocery list, supported by the same psychological and biological processes as knowing when we feel our hearts are beating rapidly as we wait at the arrivals gate for a long absent lover, or knowing that we sense impending doom as a deadline approaches for which we have not completed the work? As a first step to answer this question, we examined the relationship between knowledge about one's cognitive and bodily states using measures of metamemory and interoception.

1.1. Knowledge about cognitive states: metamemory

Metamemory, a type of metacognition, is knowledge about the contents and accuracy of one's own memory (Nelson & Narens, 1990). Metamemory is typically assessed by asking individuals to reflect on, or introspect about, their own memory

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(e.g., Chua, Schacter, & Sperling, 2009b; Ghetti, Mirandola, Angelini, Cornoldi, & Ciaramelli, 2011). Because introspections are fallible, we refer to self-reports about perceived memory ability as *metamemory beliefs*, and do not assume that these beliefs reflect accurate knowledge about memory. These beliefs can pertain to how good or bad their own memory is (e.g., "I am good at remembering names") and can also be more broad and include general beliefs about how memory works (e.g., "studying longer will help me remember") (Bennett-Levy & Powell, 1980; Dixon, Hultsch, & Hertzog, 1988; Gilewski, Zelinski, & Schaie, 1990). Metamemory beliefs can be assessed via questionnaires in which individuals report their overall beliefs about their own memory. Alternatively, they can also be assessed on a trial-by-trial basis by asking people to rate how confident, or certain, they are about specific memories, with high confidence ratings indicating they believe that they have retrieved correct information (e.g., Chua, Hannula, & Ranganath, 2012; Simons, Peers, Mazuz, Berryhill, & Olson, 2010). Comparing these metamemory beliefs to objective tests of memory yields information about the accuracy of these introspections, which is referred to as *metamemory accuracy*. In other words, metamemory accuracy provides an index of how well subjective beliefs correspond with actual memory performance. For example, an individual who is more likely to have a correct memory when he has higher confidence, and incorrect memory when he has lower confidence would have high *metamemory accuracy* because his confidence in his memory tracks his actual memory. In contrast, an individual who is equally likely to have a correct memory when she has high or low confidence would have low *metamemory accuracy* because her confidence would be a meaningless indicator of her actual memory performance. Metamemory accuracy is typically calculated using measures such as calibration, gamma, and d_a; these indices of metamemory accuracy include measures of confidence in combination with memory accuracy (Benjamin & Diaz, 2008; Masson & Rotello, 2009). While calibration, gamma, and d_a all index metamemory accuracy, their calculations are different and they tap into slightly different ways confidence can be meaningfully related to accuracy (see Section 3.1.2.1). In examining metamemory, it is critical to evaluate and understand both of these dimensions (Table 1): (1) the *metamemory beliefs*, which encompass both the confidence in one's memory for a single memory and declarative statements about one's memory and how it works and (2) *metamemory accuracy*, which is the comparison of the metamemory beliefs to actual memory performance (Chua, Pergolizzi, & Weintraub, 2014).

1.2. Knowledge about bodily states: interoception

Just like we have knowledge of cognitive states (e.g., metamemory), we also have knowledge of our bodily or physiological states, referred to as interoception (Craig, 2003). Like metamemory, interoception can broadly refer to both subjective beliefs about physiological states and the accuracy of those beliefs (Table 1) (Ceunen, Van Diest, & Vlaeyen, 2013; Garfinkel & Critchley, 2013). Parallel with metamemory measures, *interoceptive beliefs* can be indexed via retrospective self-report measures (e.g., Body Awareness Questionnaire (*BAQ*); Shields, Mallory, & Simon, 1989) and when they are, typically reflect general beliefs about capacity (for review, see Mehling et al., 2009). To measure the accuracy of interoceptive beliefs about the body, participants are generally asked to report on their physiological states in the moment (Garfinkel, Seth, Barrett, Suzuki, & Critchley, 2015). As is true of metamemory accuracy, computing *interoceptive accuracy* involves mathematically comparing people's beliefs about their bodies to some objective criteria about what their bodies are doing. The most common interoceptive tasks ask participants to count or monitor their heartbeats (Pollatos, Gramann, & Schandry, 2007; Schandry, 1981; Whitehead & Drescher, 1980; Whitehead, Drescher, Heiman, & Blackwell, 1977). It is important to note that less attention has been paid to the relationship between subjective beliefs and accuracy of interoception, compared to metamemory. Investigating the relationship between interoceptive beliefs and interoceptive accuracy is an active area of research (Garfinkel et al., 2015).

Table 1
Dimensions of metamemory and interoception in terms of beliefs and accuracy, and how they relate to Studies 1–3. Modeled off of Garfinkel et al. (2015).

	Metamemory Beliefs	Metamemory Accuracy	Interoceptive Beliefs	Interoceptive Accuracy
Definition	Self-perceived knowledge of one's own memory	Accuracy of self-perceived knowledge of one's own memory	Self-perceived ability to detect bodily sensations	Accuracy of self-perceived bodily sensations
Example	Do you think you are good at remembering names? Will studying in spaced intervals help you remember?	When you are highly confident in a memory, is it an accurate memory?	Do you think that you detect internal bodily sensations?	Can you accurately report the number of heart beats during a specific interval?
Mode of Assessment	Self-report about perceived memory ability	Relationship between objective performance and self-reported beliefs	Self-report about perceived ability to detect bodily sensations	Relationship between objective bodily sensation and perceived bodily sensation
Example	Questionnaires, such as the Metamemory in Adulthood Questionnaire; Confidence in specific memories, or average confidence in memory ability	Assessing the confidence-accuracy relationship via calibration, the gamma correlation, d_a, and meta d′	Questionnaires, such as the Body Awareness Questionnaire	Accuracy during heartbeat counting or detection tasks

1.3. Linking metamemory and interoception

While cognition is often considered to be separate or distinct from bodily processes (in the spirit of Descartes) (Gilin, Maddux, Carpenter, & Galinsky, 2013; Janssen, van Osch, Lechner, Candel, & de Vries, 2012; Schlaffke et al., 2015; Swann, Griffin, Predmore, & Gaines, 1987), there is growing recognition that in fact that cognition is "embodied" such that cognitive processes rely on neural representations of the body (Barsalou, 2008). For example, evidence from neuroimaging indicates that both metamemory (Chua, Schacter, Rand-Giovannetti, & Sperling, 2006; Chua et al., 2009b) and interoception (Critchley, Melmed, Featherstone, Mathias, & Dolan, 2002; Critchley, Wiens, Rotshtein, Ohman, & Dolan, 2004; Pollatos, Schandry, Auer, & Kaufmann, 2007) recruit the insula—a key region involved in the integration of homeostatic information and visceromotor control (Craig, 2003, 2008, 2009). It is therefore possible, even probable, that metamemory and interoception are subserved by a common neural system that involves or is anchored in the insula. Before examining a possible shared neural mechanism of these effects, it is critical first to establish a relationship between metamemory and interoception.

In the present studies, we evaluated the relationship between metamemory and interoception, and indexed both beliefs and accuracy. If a common mechanism subserves metamemory and interoception then there should be consistent and related individual differences such that performance on metamemory and interoception measures is positively correlated for both beliefs and accuracy. Across three studies, we evaluated subjective beliefs and objective accuracy of metamemory and interoception, predicting that the indices would be correlated. In other words, we asked the questions: do people who believe they have accurate knowledge of their memories also believe that they have good knowledge about reading their bodily signals, and are people who are indeed good at knowing their own memory also good at knowing their bodily signals? In Study 1, we examined the relationship between metamemory beliefs and interoceptive beliefs using self-report measures. In Study 2, we examined the relationship between metamemory beliefs related to specific memories (i.e., a performance task) and interoceptive beliefs using a self-report, while controlling for performance and confidence in other domains. Finally, in Study 3, we examined the relationship between metamemory accuracy and interoceptive accuracy. Together, these studies show a relationship between metamemory and interoception when examining both subjective beliefs and accuracy.

2. Study 1: metamemory beliefs & interoceptive beliefs

2.1. Method

2.1.1. Participants

211 Mechanical Turk (MTurk) workers (123 male and 88 female, ages 18–65) participated in this research for $1.00 remuneration. Participants were recruited via the Amazon Mechanical Turk website (www.mturk.com). MTurk workers qualified to participate if they were over 18 years of age, were located in the United States, had previously completed at least 1000 HITs that were subsequently approved, and had at least a 98% approval rate on HITs. Participant data were excluded if they failed our "catch trial". Participants were asked "How often do you have fatal heart attacks while trying to remember something?" and were excluded if they answered anything other than "never". Eleven participants were excluded and data from the remaining 200 participants were analyzed. Each participant provided consent by clicking a button on the computer, which was approved by the Human Research Protection Program (HRPP) of the City University of New York (CUNY).

2.1.2. Procedures

2.1.2.1. Metamemory questionnaire. In order measure metamemory beliefs, participants completed a subset of the Metamemory in Adulthood (MIA) questionnaire (Dixon et al., 1988), and answered questions on a 5-point Likert scale related to their knowledge and use of memory strategies (Strategy subscale), knowledge about basic memory processes (Task subscale), and the relationship between anxiety and one's own memory performance (Anxiety subscale) (Hertzog, Dixon, Schulenberg, & Hultsch, 1987). Responses were analyzed by averaging the Likert Scale responses for the Strategy, Task, and Anxiety subscales, as well as an overall average across these dimensions, which we will refer to as Overall Metamemory. Although some items were reverse scaled, scores were calculated such that: (1) for Strategy, higher numbers indicate more strategy use; (2) for Task, higher numbers indicate higher knowledge about basic memory processes; and (3) for Anxiety, higher numbers indicate higher anxiety and/or higher knowledge about how anxiety effects memory. Accordingly, higher numbers in the Overall Metamemory score indicate higher self-reported metamemory.

2.1.2.2. Body awareness questionnaire. Participants answered the 18 questions from the Body Awareness Questionnaire (Shields et al., 1989), as a measure of interoceptive beliefs. In the Body Awareness Questionnaire, participants are given several statements about their sensitivity to normal, non-emotive bodily processes. They are then asked to indicate how well the statement describes them on a 7-point Likert scale that ranges from "Not at all true of me" to "Very true of me." The questionnaire indexes sensitivity to body cycles and rhythms, the ability to predict bodily changes, and the ability to detect small changes in bodily functioning. Bodily Awareness was calculated by averaging the 1–7 responses on the scale across the 18 questions, accounting for the reversed scale item.

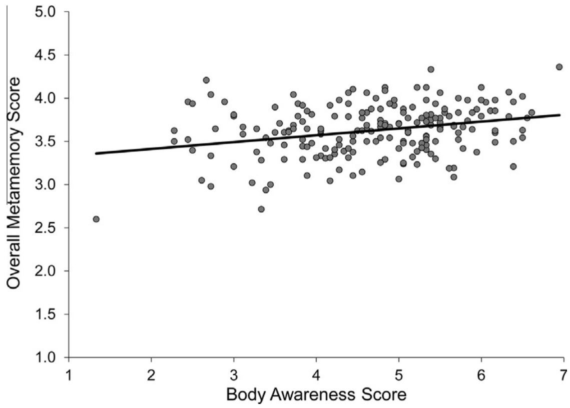

Fig. 1. Scatter plot showing that metamemory beliefs and interoceptive beliefs are correlated using self-report questionnaires (Study 1). Score on the Body Awareness Questionnaire, a measure of interoceptive beliefs, positively correlated with overall metamemory, assessed by the Metamemory in Adulthood Questionnaire, a measure of metamemory beliefs ($r = 0.38$, $p < 0.00001$).

2.1.3. Data analysis

Correlations between Metamemory and Body Awareness scores were tested in SPSS 22.0 and were considered significant at $p < 0.05$, two-tailed. Linear regression was used to examine the relationship between metamemory subscales and body awareness, and results were considered significant at $p < 0.05$, two-tailed.

2.2. Results

We first examined whether scores on the Body Awareness Questionnaire (*Mean* ± *SD*, 4.67 ± 1.06), a measure of interoceptive beliefs, correlated with our Overall Metamemory score (*Mean* ± *SD*, 3.62 ± 0.30), a measure of metamemory beliefs. There was a positive correlation ($r = 0.38$, $p < 0.00001$) such that individuals with increasing interoceptive beliefs showed increased metamemory beliefs in general (Fig. 1).

We next examined whether specific domains of metamemory were driving this correlation and used linear regression to determine if Strategy, Task, and/or Anxiety were predictive of interoceptive beliefs. Strategy was the only significant predictor of interoceptive beliefs ($R^2 = 0.150$; $R^2_{adjusted} = 0.137$; $F(3,196) = 11.50$, $p < 0.00001$; Strategy: $B = 0.854$, 95% CI [0.560, 1.15]; Task: $B = 0.233$, 95% CI [−0.143, 0.609]; Anxiety: $B = -0.039$, 95% CI [−0.241, 0.164]).

2.3. Discussion

Participants who believed themselves to be better at interoception, also reported better metamemory. This relationship was driven by self-reported meta-memory strategy use and/or knowledge about memory strategies, and not by general knowledge about memory, or anxiety about memory. The questionnaire responses in this study only provide insight metamemory and interoceptive beliefs, but no information about whether or not these beliefs are accurate. Our next step was to determine whether interoceptive beliefs were related to metamemory beliefs alone, or whether interoceptive beliefs were also related to metamemory accuracy. In Study 2, we used a combination of self-report questionnaires and performance tests to address this possibility, while controlling for confidence (a component of metamemory) in other domains.

3. Study 2: metamemory beliefs/accuracy & interoceptive beliefs

3.1. Methods

3.1.1. Participants

110 MTurk workers (48 male and 62 female, ages 18–49) participated in this research for $1.00 through the Amazon Mechanical Turk website (www.mturk.com). Inclusion and exclusion criteria, and consent procedures were the same as Study 1 (Section 2.1.1). Ten people failed our 'catch trial', and data from the remaining 100 participants were analyzed.

3.1.2. Procedures

3.1.2.1. Memory and metamemory task. Fifty general knowledge questions were selected from a database of recently normed questions (Tauber, Dunlosky, Rawson, Rhodes, & Sitzman, 2013). In an online form, participants viewed 50 general knowledge questions and had to choose between the correct answer and an incorrect answer. Participant's made their choice on a 6-point scale that incorporated confidence. Specifically, they were told that:

> "Clicking 1-3 indicates you think it is the choice on the left and clicking 4-6 indicates you think it is the choice on the right" and "The differences between 1-3 and 4-6 indicate differences in your certainty. Clicking 1 indicates you are 100% sure that it is the choice on the left, 2 indicates you are 66% sure it is the choice on the left, 3 indicates you are 33% sure it is the choice on the left, 4 indicates you are 33% sure it is the choice on the right, 5 indicates you are 66% sure it is the choice on the right, and 6 indicates you are 100% sure it is the choice on the right."

Memory accuracy was calculated as the proportion of correct answers. Metamemory beliefs were indexed by the proportion of high confidence responses given to all questions ("1" or "6" responses). We examined three different measures of metamemory accuracy: calibration (Jonsson & Allwood, 2003; Lichtenstein, Fischhoff, & Phillips, 1982), the Goodman-Kruskal gamma correlation (Nelson, 1984; Pannu & Kaszniak, 2005), and d_a (Benjamin & Diaz, 2008; Masson & Rotello, 2009). These measures are commonly used indices of metamemory accuracy, which incorporate how accurate one's memory is with differing levels of confidence across an ordinal scale, and provide and index of how well confidence corresponds with accuracy (Chua & Solinger, 2015; Luna & Martín-Luengo, 2012; Perfect, Hollins, & Hunt, 2000; Toth, Daniels, & Solinger, 2011; Weber & Brewer, 2004). Note that metamemory accuracy describes the relationship between confidence and accuracy, and combines subjective and objective aspects of memory, whereas memory accuracy is related to objective aspects of memory and indexes whether or not memory responses were correct. One measure of metamemory accuracy, confidence-accuracy calibration, provides an absolute measure of the difference between accuracy and confidence and is tied to the rating scale. Calibration was calculated using the formula: $1/n \sum n_t(r_{tm} - c_t)^2$ (Jonsson & Allwood, 2003; Lichtenstein et al., 1982), where n is the total number of trials, c_t is the proportion of correct trials for all items in the confidence rating r_t, n_t is the number of times the confidence rating r_t was used, and r_{tm} is the mean of the confidence ratings in class r_t. Perfect calibration is 0, and larger numbers represent more calibration errors, or a worse correspondence between confidence and accuracy. The gamma correlation is a relative measure of metamemory in that it assesses the degree to which participants can distinguish that they were more or less likely to have made an accurate memory decision. This measure is not tied to the numeric probabilities determined by the rating scale in absolute terms, but instead is sensitive to whether when an individual is more likely to be correct with higher confidence ratings. Larger gammas indicate better metamemory accuracy, with perfect metamemory accuracy being 1. We also calculated d_a, a signal detection theory-based measure of relative accuracy, using the formula $d_a = \sqrt{2}y_0/(1 + m^2)$ where y_0 and m^2 represent the y intercept and slope, respectively, of a normal deviate isosensitivity function (Benjamin & Diaz, 2008; Masson & Rotello, 2009). For cases in which a participant failed to use one of the confidence responses, a correction where 0 was replaced with 0.5/n (n = #trials) was applied (Stanislaw & Todorov, 1999).

3.1.2.2. Body awareness questionnaire. In the second part of the study, participants completed the Body Awareness Questionnaire (Shields et al., 1989; Section 2.1.2.2) as a measure of interoceptive beliefs.

3.1.2.3. Personal evaluation inventory (PEI). As a control task, participants were given the PEI (Shrauger & Schohn, 1995) which measures domain-specific and general confidence. This is a 54-item scale that asks whether participants "Strongly Agree", "Mainly Agree", "Mainly Disagree", or "Strongly Disagree" with statements that reflect common feelings, attitudes, and behaviors. The scale includes both positively and negatively worded items across several domains. Items assessed confidence in Academic, Appearance, Athletics, Romantic, Social, and Speaking domains, as well as general confidence and mood.

3.1.2.4. Dot estimation task. As a secondary control, we included an additional task that allowed us to compare subjective confidence with objective performance in a domain unrelated to memory or bodily processes. Specifically, we included a dot estimation task immediately following the PEI because previous research has shown that there are individual differences related to overestimation and underestimation (Izard & Dehaene, 2008). Participants were instructed to estimate the number of dots presented on a computer screen on 6 trials. Dots were white circles on a grey background. Dots were presented in random locations on the screen for 5 s using Qualtrics (qualtrics.com), or until the participant advanced the screen. The trials consisted of displays of 162, 109, 81, 203, 121, and 66 dots. After each trial, participants were instructed to rate their confidence in their decision using a sliding scale ranging from 1 to 6, where 1 represented "I am the least bit confident. My estimate is probably really different from the actual number of dots" and 6 represented "I am very confident. My estimate if probably within 10 (plus or minus) dots of the number actually on the screen."

Dot estimation accuracy was calculated using the formula: $1 - [(\sum|A_i - R_i|/A_i)/6]$, where A_i = actual number of dots during trial *i* and R_i = number of dots estimated (reported by participant) during trial *i*. A value of 1 equals perfect dot estimation.

3.1.3. Data analysis

We first ran correlation analyses to determine whether the score of the Body Awareness Questionnaire (a measure of interoceptive beliefs) related to memory accuracy, metamemory accuracy, and confidence (a measure of metamemory beliefs). We next ran correlation analyses to determine whether the score of the Body Awareness Questionnaire or the proportion of high confidence responses on the general knowledge test related to the average score on the PEI, the subscales of the PEI, dot estimation accuracy, and dot estimation confidence. Correlations were tested in SPSS 22.0 and were considered significant at $p < 0.05$, two-tailed. Next, linear regression was used to test for effects of bodily awareness on metamemory accuracy and proportion of high confidence responses while controlling for effects of memory accuracy, trait confidence, and dot estimation confidence. In a two-step model, memory accuracy, average score on the PEI, and dot estimation confidence were entered as predictors for metamemory accuracy or proportion of high confidence responses in the first model and bodily awareness was entered as a predictor in the second model.

3.2. Results

Participants performed well above chance (50%) on the general knowledge questions with an average of 80.3 ± 9.6% (*Mean* ± *SD*) correct. Over half of their responses were made with high confidence, with an average of 61.2 ± 19% of all responses being made with high confidence. Not all participants used the full response scale, resulting in Gamma being incalculable for 6 participants and Calibration being incalculable for 10 participants. Metamemory accuracy, as measured by calibration (0.026 ± 0.018), the gamma coefficient (0.75 ± 0.26), and d_a (1.31 ± 0.53), was reasonably good.

Consistent with Study 1, scores on the Body Awareness Questionnaire and proportion of high confidence responses were positively correlated ($r = 0.251$, $p < 0.012$; Fig. 2). However, the score on the Body Awareness Questionnaire was not significantly correlated with memory accuracy ($r = -0.018$, $p = 0.861$), calibration ($r = 0.045$, $p = 0.675$), the gamma coefficient ($r = -0.126$, $p = 0.229$), or d_a ($r = -0.083$, $p = 0.416$), suggesting that interoceptive beliefs do not correlate with memory or metamemory accuracy. For the full correlation matrix, see Table 2.

To test whether the relationship between interoceptive beliefs and metamemory beliefs was specific to memory, or related to a more general trait of self-confidence, we examined whether scores on the Body Awareness Questionnaire and proportion of high confidence responses correlated with responses to the PEI. Participant's scores on the Body Awareness Questionnaire were not significantly correlated with the average PEI ($r = -0.002$, $p = 0.984$), and the only subscale that approached significance was the appearance subscale ($r = 0.196$, $p < 0.052$; all other subscales $|rs| < 0.13$, all $ps > 0.19$). The same was true for the proportion of high confidence response to the general knowledge questions; there was no significant correlation with average PEI ($r = -0.022$, $p = 0.829$), or its subscales (all 8 subscales $|rs| < 0.19$, all $ps > 0.08$). Thus, it appears that the relationship between interoceptive beliefs and metamemory beliefs cannot be explained by general confidence in one's own abilities.

We next examined the specificity of the interoceptive belief and metamemory belief relationship by comparing confidence and accuracy on an unrelated task: dot estimation. The dot estimation task was indeed very different than the general knowledge task, with accuracy on the general knowledge and dot estimation tasks showing a negative correlation ($r = -0.262$, $p < 0.009$). Still consistent with a specific relationship between interoceptive beliefs and metamemory beliefs, scores on the Body Awareness Questionnaire did not correlate with accuracy on the dot estimation task ($r = -0.068$, $p = 0.503$), or confidence on the dot estimation task ($r = 0.002$, $p = 0.988$). The same was true for the proportion of high confidence response to the general knowledge questions; neither dot estimation accuracy ($r = -0.083$, $p = 0.413$), nor confidence on the dot estimation task ($r = 0.020$, $p = 0.845$) were correlated with the proportion of high confidence responses.

We used a two-step linear regression to test for effects of score on the Body Awareness Questionnaire, while controlling for memory accuracy, trait confidence using the average PEI, and task confidence using confidence in dot estimation, on the proportion of high confidence responses. The model with memory accuracy, average PEI, and dot estimation confidence was a significant predictor of proportion of high confidence responses ($R^2 = 0.336$; $R^2_{adjusted} = 0.113$; $F(3,95) = 4.035$, $p < 0.01$). Critically, bodily awareness explained additional unique variance ($R^2 = 0.423$; $R^2_{adjusted} = 0.179$; F_{change} $(1,94) = 7.559$, $p < 0.01$; memory accuracy B = 0.680, 95% CI [0.308, 1.052]; Average PEI B = −0.008, 95% CI [−0.170, 0.154]; dot estimation confidence B = 0.017, 95% CI [−0.021, 0.055]; bodily awareness B = 0.047, 95% CI [0.013, 0.081]).

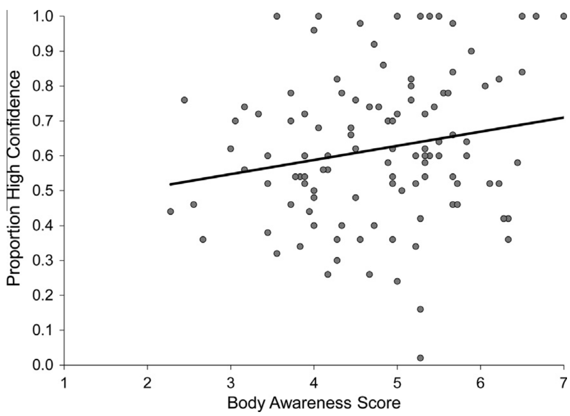

Fig. 2. Scatter plot from Study 2 showing a significant association between interoceptive beliefs, as measured by score on the Body Awareness Questionnaire and metamemory beliefs, as measured by higher confidence on the general knowledge test ($r = 0.232$, p < 0.05).

Table 2

The correlation matrix for all variables related to interoceptive beliefs, memory accuracy, metamemory beliefs, metamemory accuracy, the Personal Evaluation Inventory (PEI) and its subscales, and the dot estimation task from Study 2. Our primary interest was in factors that correlated with response on the Bodily Awareness Scale, which appears in bold. Individuals who believed they were more aware of their bodies, as measured by the Bodily Awareness Scale, also believed that they had better memories, as indicated by a significant correlation with the Proportion of High Confidence (CONF) responses. Cells that appear in grey represent correlations between measures of similar constructs (i.e., different measures of metamemory accuracy or different PEI subscales).

	Bodily Awareness	Memory Accuracy	Prop. High CONF	Calibration	Gamma	d_a	Avg. PEI	PEI: Academic	PEI: Appearance	PEI: Athletic	PEI: General	PEI: Mood	PEI: Romantic	PEI: Social	PEI: Speaking	Dot Est.	Dot CONF
Bodily Awareness	**1**																
Memory Accuracy	**.005**	1															
Prop. High CONF	**.232***	.238*	1														
Calibration	**.045**	.036	-.257*	1													
Gamma	**-.126**	.182	.058	-.274**	1												
d_a	**-.053**	.622**	.202*	-.397**	.504**	1											
Average PEI	**-.004**	-.070	-.017	.019	.223*	.047	1										
PEI: Academic	**-.113**	-.085	-.125	-.081	.0106	.124	.409**	1									
PEI: Appearance	**.197***	-.032	.042	.071	.148	.038	.653**	-.003	1								
PEI: Athletic	**.111**	-.003	-.099	.181	-.018	-.116	.570**	.218*	.347**	1							
PEI: General	**.030**	-.058	.064	-.046	.157	.078	.817**	.354**	.504**	.386**	1						
PEI: Mood	**-.130**	.041	-.12	.083	.187	-.107	.595**	.090	.237**	.215*	.453**	1					
PEI: Romantic	**-.123**	-.005	-.77	-.020	.199	-.118	.617**	.147	.308**	.243*	.441**	.334**	1				
PEI: Social	**.040**	-.251*	-.037	-.133	.109	.027	.618**	.136	.318**	.313**	.450**	.229*	.327**	1			
PEI: Speaking	**-.054**	.076	-.064	.035	.132	.103	.388**	.068	.201*	.068	.190	.144	.069	.147	1		
Dot Estimation	**-.072**	-.235*	-.086	-.153	.094	-.093	-.030	-.088	.134	-.064	-.070	.090	-.160	-.053	.016	1	
Dot Estimation CONF	**.008**	-.148	.00002	-.272**	.065	-.010	.113	.011	.192	.007	.058	.081	.069	.079	-.012	.031	1

* Correlation is significant at the $p < 0.05$ level (2-tailed).
** Correlation is significant at the $p < 0.01$ level (2-tailed).

3.3. Discussion

Studies 1 & 2 showed a link between metamemory beliefs and interoceptive beliefs, but not metamemory accuracy and interoceptive beliefs. Because the link between metamemory beliefs and interoceptive beliefs replicated across studies, and there was no evidence of a relationship between metamemory accuracy and interoceptive beliefs, we next focused on the relationship between interoceptive accuracy and metamemory accuracy. This is a critical step because a previous study demonstrated that self-report measures of interoception and interoceptive accuracy did not correlate (Garfinkel et al., 2015). Given that metamemory beliefs and interoceptive beliefs were related in Studies 1 & 2, we expected that parallel aspects of interoception and metamemory would be correlated (i.e., beliefs would correlated with beliefs, and accuracy would correlate with accuracy). In Study 3, we examined the relationship between interoceptive accuracy and metamemory accuracy.

4. Study 3: metamemory beliefs/accuracy & interoceptive accuracy

4.1. Methods

4.1.1. Participants

Thirty-six English speaking Brooklyn College students (5 male and 35 female, ages 18–35) participated in this research for course credit (1 credit for 1 h of participation). Participants were recruited via the Brooklyn College Psychology Department Research Participation website. Participants were excluded if they had a known history of irregular heartbeats. Participants were instructed not to exercise within 2 h of the start of their session, to refrain from drinking caffeine within 5 h of the start of their session, and to abstain from drinking alcohol within 12 h of the start of their session. Data from a total of 6 participants were excluded from analyses; 3 were excluded based on programming errors, 2 were excluded for failing to use the full response scale in the metamemory task, which makes the metamemory accuracy measures impossible to accurately calculate, and 1 participant was excluded for falling asleep during encoding. Thus, data from 30 participants were analyzed in this Experiment. Each participant provided written consent form in a manner approved by the Human Research Protection Program at Brooklyn College.

4.1.2. Interoceptive accuracy

Interoceptive accuracy was measured based on the heartbeat perception task (Schandry, 1981). In this task, participants count the number of heartbeats they have during short set periods of time, without physically feeling for their pulse or heartbeat. Interoceptive accuracy is then computed by comparing participants' reports of their heart rate to their actual heart rate. This task has been used to assess interoceptive accuracy in many studies (Dunn, Dalgleish, Ogilvie, & Lawrence, 2007; Pollatos & Schandry, 2004; Ring & Brener, 1996), and correlates with heartbeat detection tasks (Knoll & Hodapp, 1992), such as the Whitehead task (1977).

Heartbeat data were collected using a PowerLab 8/30 system by ADInstruments with an electric pulse transducer using Chart 5 software (Dunedin, New Zealand). The session began with the participant sitting in an armchair resting for 5–10 min. Participants were instructed to turn their focus inward and to sense their heartbeat without using their hands to feel their heart or pulse. Participants were instructed to begin counting their heartbeats at the start signal and end counting at the stop signal. Trials were 25, 35, and 45 s long. After each stop signal, participants reported the number of heartbeats they believed to have occurred during the previous period to the experimenter.

Actual heartbeat counts were calculated from the pulse data using LabChart7 (ADInstruments, Dunedin New Zealand). Integrity and accuracy of the pulse data was assured based on visual inspection of the data for any artifacts that would alter the pulse counts. In this experiment, all participants had adequate pulse data for accurate pulse counts. Interoceptive accuracy was calculated using the formula: $1 - [(\sum|A_i - R_i|/A_i)/3]$, where A_i = number of actual heartbeats during trial i and R_i = number of heartbeats counted (reported by participant) during trial i. A value of 1 equals perfect heartbeat detection.

4.1.3. Metamemory accuracy

Stimuli consisted of 150 photographs of faces presented on a neutral background with neutral facial expressions (Minear & Park, 2004). There were equal numbers of male and female faces that represented a range of ages from young to older adults with a variety of racial and ethnic backgrounds. Faces were paired with 150 first names selected from the Social Security website indexing popular names by year. During the study phase, participants viewed faces on a grey background paired with a first name written in white underneath the face. Each face-name pair was presented for 4 s. The memory test consisted of a 3-alternative forced choice recognition task for the name associated with the face. Participants viewed the face with 3 different names underneath (1 correct, 2 incorrect). The 2 incorrect names had been paired with other faces during study so that participants could not solve the task using name familiarity alone. Following recognition, participants indicated their confidence that they had chosen the correct name on a 3-point scale (high, medium, and low). Participants were tested on one-third of the face-name pairs that they studied so that there were no repeated names during test, for a total of 50 test trials. The specific face-name pairs seen at test were counterbalanced across participants. The memory test was self-paced.

Stimuli were presented and behavioral responses were collected using PsychoPy 1.73 (Peirce, 2007) on a Dell Optiplex GX620.

Metamemory accuracy was calculated by relating confidence and accuracy on the recognition test using the same methods as Study 2 (Section 3.1.2.1).

4.1.4. Data analysis

Our primary interest was in examining whether interoceptive accuracy and metamemory accuracy measures were related. Correlations were tested in SPSS 22.0 and were considered significant at $p < 0.05$, two-tailed. Next, linear regression was used to test for effects of interoceptive accuracy on metamemory above and beyond effects of memory accuracy. In a two-step model, memory accuracy was entered as a predictor for metamemory accuracy in the first model and interoceptive accuracy was entered as a predictor for metamemory accuracy in the second model.

4.2. Results

Overall, participants performed above chance (33%) on the memory task. There was a satisfactory range of scores on interoceptive accuracy, memory accuracy, confidence-accuracy calibration, gamma, and d_a, suggesting that this sample's memory processes were comparable to previous samples (Chua et al., 2006, 2009b). See Table 3.

Our primary interest was whether interoceptive accuracy was related to metamemory accuracy, or memory accuracy. Table 4 shows the correlation matrix for interoceptive accuracy, memory accuracy, calibration, gamma and d_a. Of our metamemory and memory measures, only calibration was significantly correlated with interoceptive accuracy (Fig. 3).

Table 3
Descriptive statistics for interoceptive, memory, and metamemory measures.

	Mean	SD	Min	Max
Average Heart Rate (beats/min)	81.12	10.73	62.17	104.72
Interoceptive Accuracy	0.68	0.17	0.39	0.97
Memory Accuracy	0.50	0.10	0.34	0.72
Confidence-Accuracy Calibration	0.072	0.057	0.0082	0.26
Gamma	0.48	0.25	−0.07	0.92
d_a	0.67	0.40	−0.09	1.35

Table 4
Correlation matrix for measures of interoception, memory accuracy, and metamemory accuracy.

	Interoceptive Accuracy	Recognition Accuracy	Calibration	Gamma	d_a
Interoceptive Accuracy	1				
Memory Accuracy	0.282	1			
Calibration	−0.45*	−0.71**	1		
Gamma	0.34*	0.61**	−0.74**	1	
d_a	0.22	0.52**	−0.66**	0.91**	1

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.001 level (2-tailed).

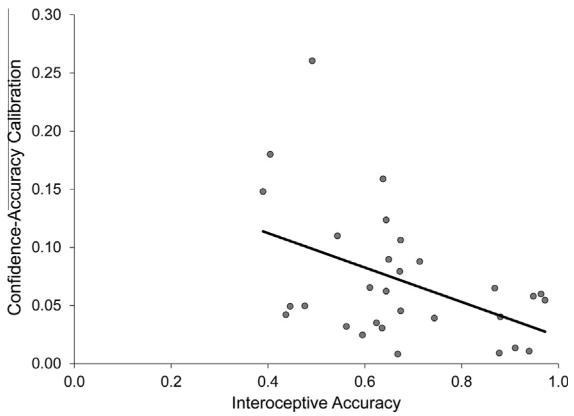

Fig. 3. Scatter plots showing that interoceptive accuracy is negatively correlated with metamemory accuracy, as measured by confidence-accuracy calibration ($r = -0.45$, $p < 0.05$). Note perfect calibration is zero, so the negative relationship is expected.

Participants who had higher confidence-accuracy calibration (lower numbers) had higher interoceptive accuracy (higher numbers).

Because interoceptive accuracy and memory accuracy both correlated with calibration, we used a two-step linear regression to test for effects of interoceptive accuracy, while controlling for memory accuracy, on confidence-accuracy calibration.

Memory accuracy was a significant predictor of confidence-accuracy calibration ($R^2 = 0.504$; $R^2_{adjusted} = 0.486$; $F(1,28) = 28.45$, $p < 0.0001$), and interoceptive accuracy explained additional variance ($R^2 = 0.574$; $R^2_{adjusted} = 0.542$; F_{change} $(1,27) = 4.43$, $p < 0.05$; memory accuracy B = −0.38, 95% CI for B [−0.54, −0.22]; interoceptive accuracy B = −0.09, 95% CI [−0.18, −0.002]).

4.3. Discussion

Study 3 showed that interoceptive accuracy correlates with metamemory accuracy, when controlling for memory accuracy. Although this sample is somewhat small, post hoc power analyses in R (R Core Team, 2013) using the package *pwr* (Champely, 2015) indicated that the present study was powered at 82.70% for a one sided test and 73.27% power for a two-sided test. Future work should replicate this effect using a larger sample.

Only one metamemory accuracy measure, confidence-accuracy calibration, correlated with interoceptive accuracy. However, it is worth noting that gamma correlated with calibration, and the correlation between gamma and interoceptive accuracy approached significance ($p < 0.065$). One possible explanation for why calibration was the only measure of metamemory accuracy that correlated with interoceptive accuracy might be that interoceptive accuracy and confidence-accuracy calibration are absolute measures (i.e., they reflect how well the subjective ratings estimate objective performance and are tied to the rating scale), while gamma and d_a are not tied to the rating scale. Although this study did not include additional control tasks (such as the dot estimation task), the relationship between metamemory accuracy and interoceptive accuracy remained when controlling for memory accuracy, suggesting a distinct relationship between metamemory accuracy and interoceptive accuracy. Furthermore, in Study 2, there was no relationship between dot estimation accuracy, memory accuracy, and metamemory accuracy, leading us to infer that it is unlikely metamemory accuracy and interoceptive accuracy are related because of a general ability to succeed at all tasks. Nevertheless, future work should include additional non-memory control measures, as well as questionnaire measures of metamemory and interoception.

5. General discussion

Three studies provide initial evidence that knowledge of our minds and bodies are related, using both self-report and performance methods. These findings suggest that there may be a common mechanism underlying different aspects of self-knowledge: knowing the content of your mental processes, in the case of metamemory, and your peripheral physiological state, in the case of interoception. Using questionnaire measures, Study 1 demonstrated that interoceptive beliefs were positively correlated with metamemory beliefs. Converging evidence emerged using an interoception questionnaire and a trial-by-trial metamemory test in Study 2; interoceptive beliefs again correlated with metamemory beliefs, and remained when controlling for a general confidence effect. Finally, in Study 3, interoceptive accuracy and metamemory accuracy, as measured by confidence-accuracy calibration, were related such that individuals with higher interoceptive accuracy also had better calibration. Taken together, the effect documented in these studies suggests that parallel dimensions of metamemory and interoceptive are related, and therefore, may share a common underlying mechanism.

Work on metamemory (Chua et al., 2014) and interoception (Garfinkel et al., 2013, 2015) have independently emphasized the need to understand multiple dimensions of these constructs, and our current work ties them together in a novel way. For metamemory, two dimensions are: (1) metamemory beliefs, which are self-perceptions about one's memory, often measured by the level of confidence expressed or general beliefs about capacity and (2) metamemory accuracy, which is the accuracy of those beliefs (Chua et al., 2014). For interoception, two dimensions are: (1) interoceptive beliefs, which are self-perceptions about one's sense of the body and (2) interoceptive accuracy, which is how well an individual performs on objective interoceptive tasks (Garfinkel et al., 2013, 2015). Across our different studies, there were significant correlations between our interoception measures and our metamemory measures, and these were seen only within the corresponding dimensions (i.e., beliefs correlated with beliefs, but not accuracy; accuracy correlated with accuracy), and were not reducible to a general confidence effect. These results indicate that metamemory and interoception are related, and that this relationship is specific to the dimension of the construct being measured.

Our findings are also consistent with classic theories of self-awareness. Classic theories of self-awareness – reflective, conscious awareness of one's self – posit that awareness arises from the comparison of one's own actions, beliefs, and experiences to a criterion or standard (Carver & Scheier, 1981; Duval & Wicklund, 1972; Silvia & Gendolla, 2001; Wicklund, 1980). Such self-awareness likely emerges from the coordinating activity of multiple neural regions that subserve complementary roles in the processing. One candidate anatomical hub for this mechanism is the insula. Insula activity has correlated with both interoception (Critchley et al., 2004; Pollatos, Gramann, et al., 2007; Zaki, Davis, & Ochsner, 2012) and metamemory (Chua et al., 2006; Kikyo & Miyashita, 2004; Moritz, Gläscher, Sommer, Büchel, & Braus, 2006) and is thought to play a broad role in the representation of affective information (Craig, 2009). Another possible hub is the anterior cingulate cortex (ACC), which like the insula, has been implicated in interoception (Critchley et al., 2002, 2004; Pollatos, Schandry, et al., 2007) and metacognition (Chua, Schacter, & Sperling, 2009a; Chua et al., 2006). Ventral medial prefrontal cortex (vmPFC) is also a candidate brain region for the network because it has shown to be critical for accurate metamemory in lesion studies (Modirrousta & Fellows, 2008; Schnyer et al., 2004) and which shows greater activity with greater metamemory accuracy in fMRI studies (Schnyer, Nicholls, & Verfaellie, 2005). The vmPFC has also shown to be critical in using affective information to guide behavior (Damasio, 1996). Furthermore, fMRI studies have also shown that activity in the mPFC correlates with self-referential thinking (Jenkins & Mitchell, 2011; Saxe, Moran, Scholz, & Gabrieli, 2006) and is implicated if a broad array of affective experiences (for a meta-analytic review: Lindquist, Wager, Kober, Bliss-Moreau, & Barrett, 2012). With these three anatomical hubs as starting places, future work will investigate the neural mechanisms that subserve the relationship between metamemory and interoception.

One interpretation of our data – that knowledge of one's cognitive and bodily processes are related – is that both processes rely on a common mechanism. However, our data cannot rule out the alternative explanation that metamemory signals are based, at least in part, on peripheral psychophysiological signals. In this view, participants would use bodily signals to make decisions about whether their memories are accurate. Indeed, there is some evidence that metamemory may be embodied in this way. For example, in one study used physical weight as an embodied cue for importance, and showed that stimuli with greater weights were given higher metacognitive ratings (Alban & Kelley, 2013). Another embodied metacognition study showed a similar effect - contracting one's eyebrows embodied a feeling of effort and led to lower subjective ratings (Koriat & Nussinson, 2009), again showing that the bodily state can impact metacognitive judgments. Similarly, Goldinger and Hansen (2005) showed that a subliminal somatic cue (a buzz) led to increased confidence in false alarms and decreased confidence in hits, suggesting that peripheral physiological signals in combination with mnemonic information give rise to confidence. In this view, interoception and metamemory are correlated because metamemory relies on embodied processing that is made possible by interoceptive processes.

6. Conclusion

The present report takes the first step in understanding how unified self-knowledge emerges, by documenting the relationship between cognitive and bodily self-knowledge. Future work will investigate the causal nature of this relationship – whether, in fact, metamemory and interoception share a mechanism or whether one process is driven by the other. Understanding common mechanisms that shape self-knowledge may be important for understanding diseases processes that relate to self-knowledge of memory and affect, such as anosognosia in dementias (Cosentino, Metcalfe, Butterfield, & Stern, 2007; Cosentino, Metcalfe, Steffener, Holmes, & Stern, 2011) and emotion-related psychopathology (Paulus & Stein, 2006), respectively. Future work will pursue investigations of these mechanisms.

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