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Domain-specific and domain-general processes underlying metacognitive judgments.

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Abstract

Metacognition and self-awareness are commonly assumed to operate as global capacities. However, there have been few attempts to test this assumption across multiple cognitive domains and metacognitive evaluations. Here, we assessed the covariance between "online" metacognitive processes, as measured by decision confidence judgments in the domains of perception and memory, and error awareness in the domain of attention to action. Previous research investigating metacognition across task domains have not matched stimulus characteristics across tasks raising the possibility that any differences in metacognitive accuracy may be influenced by local task properties. The current experiment measured metacognition in perceptual, memorial and attention tasks that were closely matched for stimulus characteristics. We found that metacognitive accuracy across the three tasks was dissociated suggesting that domain specific networks support an individual's capacity for accurate metacognition. This finding was independent of objective performance, which was controlled using a staircase procedure. However, response times for metacognitive judgments and error awareness were associated suggesting that shared mechanisms determining how these meta-level evaluations unfold in time may underlie these different types of decision. In addition, the relationship between these laboratory measures of metacognition and reports of everyday functioning from participants and their significant others (informants) was investigated. We found that informant reports, but not self reports, predicted metacognitive accuracy on the perceptual task and participants who underreported cognitive difficulties relative to their informants also showed poorer metacognitive accuracy on the perceptual task. These results are discussed in the context of models of metacognitive regulation and neuropsychological evidence for dissociable metacognitive systems. The potential for the refinement of metacognitive assessment in clinical populations is also discussed.

Key words: Metacognition; self-awareness; confidence judgments; error monitoring; decision making; prefrontal cortex.

1.1 Introduction

Just as the accuracy of objective performance varies substantially among individuals (Kirchhoff & Buckner, 2006; Song et al., 2011), so too does the accuracy of metacognitive judgments that self-evaluate performance (Rounis, Maniscalco, Rothwell, Passingham, & Lau, 2010). Metacognition has been concieved as self-directed control processes that guide everyday decision making (Flavell, 1979; Nelson & Narens, 1990; Koriat & Goldsmith, 1996; Smith et al., 2003). For example, a lack of confidence following one's own memory retrieval often redirects behaviour, such as reallocation of study time during learning and changes of retrieval strategy (Nelson & Narens, 1990). Metacognition and awareness are often considered to be global phenomena (Shimamura, 2000). One way that metacognition is widely measured is through Retrospective Confidence Judgments (RCJs) of performance and are elicited by asking an individual to give an additional report or commentary over their initial task response. Recent research has demonstrated a distinct relationship between accuracy in retrospective judgments of performance in perceptual decision making and the anatomical structure of the anterior prefrontal cortex

(Baird et al., 2013; Fleming, Weil, Naghy, Dolan & Rees, 2010). Similar neuroanatomical regions have also been implicated in error monitoring processes, research has implicated the dorsal ACC, rostral ACC, posterior medial frontal cortex, anterior medial frontal cortex and prefrontal cortex in error awareness (Taylor,Sern & Gehring, 2007).

Furthermore, covariation between metacognitive accuracy across different tasks has lent support to a domain general account (Song et al., 2011; McCurdy et al., 2013). Sherer, Hart, Whyte, Nick, and Yablon (2005) found that the number of brain lesions rather than the volume or location was predictive of the degree of Impaired Self Awareness (ISA) in a sample of 91 participants with Acquired Brain Injury (ABI). However, recent research (Fleming, Ryu, Golfinos & Blackmon, 2014) showed that patients with lesions to the anterior prefrontal cortex (aPFC) showed a selective deficit in perceptual metacognitive accuracy but that metacognitive capacity on a memorial task remained unimpaired. In a similar vein, McCurdy and associates (2013) reported that grey matter volume in the aPFC predicted individual differences in the accuracy of decision confidence judgments in a visual discrimination task. Metacognitive accuracy in a memory recognition task on the other hand, was predicted by grey matter volume in a neuroanatomically distinct region in the medial parietal cortex. However, the extent to which domain specific metacognitive processes can be separated in studies employing psychophysical tasks with differential types of stimuli and paradigms is unclear. Convergent evidence from recent structural and functional imaging studies in support of the role of aPFC in metacognitive ability utilised tasks that permit the comparison of results across research. One possibility is that differences between the tasks could be potentially orthogonal to the domain in question. For example, Kao, Davis and Gabrieli (2005) found that Judgments of Learning (JOLs) were associated with activation in left ventromedial prefrontal cortex. A Judgment of learning elicits a belief during learning about how sucessful recall will be for a particular item on subsequent testing and is commonly used in metamemory research. On the other hand, Do Lam and colleagues (2012) observed an association with activation in medial PFC, orbital frontal, and anterior cingulate cortices and JOLs. Although ventromedial cortex activation was common to both studies, additional areas of activation were observed by Do Lam et al. (2012). Differences in activation may be due to underlying procedural differences across the two studies. Kao et al. (2005) had participants make JOLs on scenic images for eventual recognition whereas Do Lam and researchers (2012) had participants make JOLs on photographs of faces for eventual cued recall of names. Thus, variations in task design meant JOLs were based on different sources of information and thus different areas of brain activation.

Here, we compared intraindividual variability in metacognitive capacity for perceptual decisions, memorial judgments and awareness of errors controlling the nature of the stimuli across tasks in order to isolate metacognitive accuracy from changes in primary task performance. A central aim of this study was to investigate metacognition and awareness across three different cognitive paradigms, which require participants to evaluate the accuracy of their perceptions, actions and memories separately. In order to achieve this aim, novel tasks were designed to measure subjective confidence judgments for perceptual and memorial decisions, and to measure awareness of simple action errors. Each task drew upon the same set of verbal stimuli to ensure that the 'object of awareness' was constant across domains. In addition, the tasks had built in staircases applied to control for accuracy and dissociate task performance from the meta-level judgment. Furthermore, for our decision confidence tasks, we also employed a signal detection measure, the theoretic measure meta-*d'/d'* (Maniscalco and Lau, 2012). Meta-d'/d' quantifies the efficiency with which confidence ratings discriminate between correct and incorrect trials in each task domain separately (visual and memory). Using this measure of metacognition effectively eliminates performance and response bias confounds that typically affect other measures (Barrett et al., 2013).

Researchers have begun to investigate the metacognitive processes in decision making, focusing in particular on both confidence judgments and error monitoring (Yeung and Summerfield, 2014). This research will investigate the relationship between two important metacognitive evaluations-error detection and confidence judgments. Both aspects of metacognition have been studied however; very little research has focused on looking at the relationship between these two evaluations. A recent electroencephalography (EEG) study conducted by researchers Boldt and Yeung (2015) observed a clear graded modulation of error related EEG activity by confidence, suggesting that shared mechanisms underlie both aspects of metacognition. Yeung and Summerfield (2012) put forward the hypothesis that there are crucial points of convergence between these two related aspects of metacognition- error monitoring and confidence judgments. The researchers suggest that common principles govern metacognitive judgments of confidence and accuracy. In particular, a shared reliance on post decisional processing within the systems responsible for the initial decision.

Laboratory tests to assay metacognition may prove to be useful in the assessment of impairments of awareness in brain injury patients or older adults at risk of dementia. An important question is whether our capacity to evaluate different cognitive processes in the laboratory is associated with our awareness in daily life. A final aim was therefore to assess metacognitive knowledge of daily functioning in both participants and close informants (relatives or friends) and examine the relationship between these reports and laboratory measures of metacognition.

2.0 Methods

2.1Participants

Thirty participants (25 females; age range 18-62; mean age 41) took part in this study. Exclusion criteria for all participants included a pre-trauma history of epilepsy or other neurological condition, a history of major psychiatric disorder, or a history of drug or alcohol problems. They also had to have an informant (17 females, 14 males) who was a first-degree family member (spouse or partner, adult child, sibling or parent; n=23) or close friend (n=7) who could verify that they knew the participant either very (n=19) or pretty well (n=11). The Trinity College School of Psychology Ethics Committee approved the study and all participants gave informed consent prior to participation in accordance with the guidelines of the Declaration of Helsinki. All participants had normal or corrected to normal vision and hearing.

Participants were administered a neuropsychological test battery and tests designed to measure core variables in awareness assessing cognitive function in the domains of language, visuospatial function, working memory, processing speed, memory, and attention/set shifting.

2.2 Neuropsychological Measures

Neuropsychological measures administered to all participants included: the *Repeatable Battery for the Assessment of Neuropsychological Status* (RBANS; Randolph, 1998) and the *National Adult Reading Test* (NART; Nelson, 1982; Nelson & Willison, 1991). The RBANS comprises 12 subtests measuring attention, language, visuospatial/constructional abilities, and immediate and delayed memory. It was developed for the dual purposes of identifying and characterizing abnormal cognitive decline in the older adult and as a neuropsychological screening battery for younger populations. In the standardization sample (Randolph, 1998), the RBANS index scores demonstrated robust convergent validity with other neuropsychological measures including the WAIS-III (Wechsler, 1997), WMS-III, Boston naming test (BNT; Kaplan et al., 1983), judgment of line orientation (Benton et al., 1983) and verbal fluency tests. The NART contains 50 irregular words, which are read aloud and scored for accuracy. It provides an estimation of premorbid IQ based on the WAIS-R and been validated in both clinical and nonclinical populations (Bright et al., 2002 Crawford et al., 2001; Watt & O'Carroll, 1999).

2.3 Measures of Self-Awareness

The *Cognitive Failures Questionnaire* (CFQ; Broadbent et al., 1982) is a 25–item scale that includes statements relating to levels of attentional control in daily life. It has been employed in a broad range of clinical and nonclinical populations and has high construct validity (e.g. Larson et al., 1997; Wallace & Vodanovich, 2003). Research indicates that the CFQ is strongly correlated with objective indices of attention but not correlated with general intelligence (Manly, Robertson, Galloway & Hawkins, 1999; Tipper & Baylis, 1987). Suggesting it's utility as a measure of attentional control, rather than global cognitive function. Higher CFQ scores indicate poorer perceived attentional control.

The *Memory Functioning Scale* (MFS; Clare et al., (2002) is a 13-item measure that assesses an individual's subjective views of everyday memory functioning. The MFS also has a parallel informant scale (MFS-I), which elicits a separate rating of memory functioning in relation to the same specified aspects of everyday memory functioning as the MFS-S. Higher MFS scores indicate better-perceived memory functioning.

In the current study, we also use two discrepancy methods to index awareness across all measures. In line with previous informant report studies, we estimated degree of discrepancy by subtraction of " self" minus " other" ratings to derive a metacognitive estimate of awareness. We also calculated a corrected discrepancy score, which divides the self-other discrepancy by the mean of the two ratings, based on the calculations of Clare and colleagues (2010). In this study, we adopted this approach to control for between-group differences in the ratings of participants and their significant-others. This approach is recommended as it takes into account between-group differences in ratings.

Scores close to zero indicate good agreement between the participant and informant. Positive scores arise where participants rate themselves more positively than do their informants (overestimation) and negative scores arise where participants rate themselves less positively than do their informants (underestimation).

2.4 Behavioral Protocols

Three psychophysical paradigms were employed in this research designed to measure behavioral performance in the domains of sustained attention/awareness of error, decision confidence in memory and perceptual decision-making. All instructions and stimuli were presented using the ‘Presentation’ software suite (NBS, San Francisco, CA). All stimuli were presented in a pseudo-random order and word lists were counterbalanced across participants. Stimuli appeared in white font 0.25^{o} over a white fixation cross and on a grey background. Participants sat at a computer at a comfortable viewing distance. They were also instructed to maintain fixation at the fixation cross during task performance in order to minimize eye movements.

2.4.1 Error Awareness Task

The Error Awareness Task (referred to from now on as EAT) developed by Hester and colleagues (Hester et al., 2005; Hester et al., 2012) is a go/no-go response inhibition task where participants are presented with a serial stream of single colour words, with congruency between the semantic meaning of the word and its font colour manipulated across trials. This research employed a modified version of this task whereby participants are trained to respond with a single, speeded left mouse button press in situations in which a word is presented on screen (Go trial) and to withhold this response when either of two different scenarios arise: (a) when the word presented on the current trial was the same as that presented on the preceding trial (Repeat No-go trial), and (b) when the word is a palindrome word (spells the same forwards and backwards for example, the word ‘dad’ would be categorized as a palindrome (Palindrome No-go trial). In the event of a commission error (failure to withhold to either of these No-go trials), participants are trained to signal their “awareness” by making a right mouse button press. Speeded error presses can provide a trial-by-trial measure of the timing of error awareness. In addition, participants were instructed to perform the task ‘as quickly and as accurately as possible’.

Concerns that group differences could potentially be a product of group differences in the numbers of errors made, a staircase procedure that adaptively modified levels of difficulty was integrated into the task. The staircase adaptively modified levels of difficulty by checking the participants’ accuracy over consecutive blocks of 20 trials and adapting the stimulus duration and inter stimulus interval (ISI) accordingly. The first 20 stimuli of the task were presented 750ms with ISI of 1250ms. The stimulus duration subsequently remained at 750ms as long as accuracy on the previous 20 trials was between 50%-60%. If accuracy exceeded 60% the stimulus duration on screen decreased to 500ms and ISI was set at 1000ms. If accuracy fell below 50% stimulus duration was set to 1000ms with an ISI of 500ms. This evaluation and task adjustment occurred every 20 trials after. The task consisted of 120 trials, 18 of which were no-go trials (15 Repeat No-go's and 4 Palindrome No-go's).

Before testing, practice trials for each task were given to familiarize and ensure that participants were comfortable with signalling errors. Participants were presented with a sequence of 16 trials interceded by both Repeat No-go stimuli and Palindrome No-go stimuli. Participants were asked to try to withhold responding on No-go trials and to signal any errors if committed. In the event of any persisting problems in task performance during the practice session (low accuracy/ no awareness press to errors), the entire training protocol was repeated. The large majority of participants were able to complete the practice session without repetition.

Figure 1 here

2.4.2 Decision Confidence Tasks

The memory task consisted of the following sequence of events. Participants were presented with 60 English words in a pseudo randomized sequential order. Words are presented on screen above a white fixation crosshair and participants were asked to memorise as many as possible from the word list presented. Words were randomly presented on screen for 1,2 or 3 s durations. Words were generated using the Medical Research Council Psycholinguistic Database (Wilson, 1988). Each word was four to eight letters long, had one to three syllables, and had familiarity, concreteness and imagability ratings between 400 and 700. Following the study phase, participants completed a series of 2 alternate old/new judgments. Participants were instructed to indicate if they thought the word that appeared on screen was a word from the previous memory list or a new word. If the word on screen was a word from the memory list, the participant should press the 'right arrow' key. If the word on screen was a new word not on the memory list, the participant should press the 'left arrow' key. The order of study times was randomised (1, 2 or 3 s study time) and word lists were counterbalanced between participants. In total, each participant completed 120 memory trials (60 new words/60 old words).

The perceptual task followed the same protocol developed by Fleming (Fleming & Dolan, 2010). Following presentation of a lexical stimulus, participants were asked to decide whether a heavily masked stimulus was a word or non-word. Similar to the memory task, 60 Words were generated using the Medical Research Council Psycholinguistic Database (Wilson, 1988). Each word was four to eight letters long, had one to three syllables, and had familiarity, concreteness and imagability ratings between 400 and 700. A related set of pronounceable non-words was created by a random vowel change. Responses to indicate a Real-word were made using the 'right arrow' key and for a non-word using the 'left arrow' key. The duration of the stimulus presented on screen was titrated such that each participant's performance was maintained at a constant level. The aim of the staircase procedure was to equate the difficulty of the perceptual task between individuals. The staircase adaptively modified levels of difficulty by checking the participants' accuracy over consecutive blocks of 20 trials and adapting the stimulus duration accordingly. The first 20 stimuli of the task were presented for 40ms. The stimulus duration subsequently remained at 40ms as long as accuracy on the previous 20 trials was above 60%-70%. If accuracy exceeded 70% the stimulus duration on screen decreased to 20ms. If accuracy fell below 60% stimulus duration was set to 60ms. This evaluation and task adjustment occurred every 20 trials after. In total, each participant completed 120 trials (60 real words/60 non-words).

On each trial on both the perceptual and memory tasks, participants were presented with a 6-point likert confidence scale. The scale ranged from 1 (low confidence) to 6 (high confidence) and participants were encouraged to use the whole scale. Responses for the confidence scale were made using the numbers 1 to 6 on the lower right hand side of the keyboard. The confidence scale accepted participants input for 3 seconds. Participants received no feedback during the main experiment about their responses. Task order (perception and memory) was counterbalanced between participants.

Before the main tasks, participants were provided with practice blocks. Each participant was provided with a standardized set of instructions and practice protocol in 2 separate steps. First, participants were presented with example stimuli and asked to make speeded presses without confidence ratings. This section was designed to familiarize the participant with the task. The second phase consisted of 10 practice trials that simulated the main task such that participants became familiar with indicating their confidence. For the memory task there were 5 practice trials (both responses and confidence ratings) without requiring word list memorization. It was ensured that all subjects were well practiced and fully understood the requirements of the task prior to performing the main tasks.

Figure 2 here

3.0 Statistical Analysis

Statistical tests consisted of bivariate correlations (Pearson's r), paired samples t-tests and repeated measures analysis of variance (ANOVAs) where appropriate. Greenhouse-Geisser corrected degrees of freedom were used in cases of violated sphericity with corrected p-values reported.

Performance was quantified as the percentage of correct responses in each task. To estimate metacognitive efficiency meta-d' was computed (Maniscalco and Lau, 2012). In a signal detection theory framework meta-d' is a measure of type 2 sensitivity (i.e. the degree to which a subject can discriminate correct from incorrect judgments) that is expressed in the same units as type 1 sensitivity (*d'*). This approach dissociates a subject- and a domain-specific metacognitive efficiency parameter (meta-*d'*/*d'*) from both objective task performance and subjective confidence (which both vary on a trial-by-trial basis).

Type 2 Roc Curves were constructed for each participant on the perceptual task that characterized the probability of being correct for a given level of confidence. Type 2

Receiver Operating Characteristic (ROC) Curves reflect the relationship between the accuracy of discriminations and the observer's confidence rating. ROC Curves were anchored at [0,0] and [1,1]. To plot the ROC, each level of confidence *i, p(*confidence= *i* | correct*) and p*(confidence = *i* | incorrect) was calculated. To investigate whether A*roc* scales with type 1 d' performance, analysis on individual differences in metacognitive ability were examined. As mentioned above, through an adaptive staircase, variability in d' in the perceptual task was deliberately minimized through an adaptive staircase.

Controlling for type 1 performance by experimental design in a recognition memory paradigm however, poses serious methodological challenges therefore quantification of metacognitive accuracy in the memory task required a computational approach that explicitly accounts for type 1 performance. A model-based SDT approach to account for variance in primary task performance in the computation of type 2 sensitivity has been described and validated (Maniscalco and Lau, 2012). Briefly, this approach exploits the link between type I and type II SDT models to express observed type II sensitivity at the level of the type I SDT model (termed meta d'). Maximum likelihood estimation is used to determine the parameter values of the type I SDT model that provide the best fit to the observed type II data. A measure of metacognitive ability that controls for differences in type I sensitivity is then calculated by taking the ratio of meta *d'* and the type I sensitivity parameter *d'*: M_{ratio} = meta d'/d' and $M_{difference}$ = meta-*d'* - *d'*. For an ideal SDT observer, meta-d''=d'; for suboptimal metacognitive sensitivity, meta-d'<d'; and for an observer whose confidence ratings are not diagnostic of judgment accuracy at all, meta-d'=0. Any instance where $M_{difference} \neq 0$ or $M_{ratio} \neq 1$ implies a deviation of type 2 sensitivity from expectation that is not attributable to type 1 performance or type 2 response bias (provided the standard SDT assumptions hold). The most straightforward approach to computing M_{ratio} and $M_{difference}$ involves an equal variance SDT model in which the variances of internal distributions of evidence for "old" and "new" in the type I model are assumed to be equal.

4.0 Results

4.1 Controlling for performance, are there Individual differences in metacognitive sensitivity?

To investigate individual differences in metacognitive sensitivity an adaptive staircase was utilized, in which variability in d' (objective first-order task performance) was deliberately minimized, thus isolating variability in metacognitive sensitivity, that might otherwise be obscured by significant covariation with type 1 performance.

Table 1 here

As a verification that M_{ratio} was not confounded by the basic task performance, analysis confirmed that metacognitive ability in both the perceptual decision task (A_{roc}) and memory recognition task (M_{Ratio}) were uncorrelated with type 1 performance (A_{roc}: r (30)=. 268,p=. 152; M_{Ratio}: r (30)=-.241,*p*=. 200), or percentage correct (A_{roc}: r (30)=. 330,p=. 075; M_{Ratio}: r (30)=-.118,p=. 535).

As mentioned above, through an adaptive staircase, variability in objective performance in the Error Awareness Task (EAT) was deliberately minimized through an adaptive staircase. In the EAT, paired samples t-tests revealed that there were no significant differences across no-go conditions (repeat trials vs. palindrome trials) on total errors of commission (*t* (29)=. 297,p=. 769), aware errors (*t* (29)=-.839,*p*=. 408) or unaware errors (*t* (29)=1.83,*p*=. 078). Indicating that there were no differences in condition difficulty in the error awareness task. As a further verification that Error Awareness was not confounded by the basic task performance, analysis confirmed that it was uncorrelated with type 1 objective performance (r (30)=. 267,p=. 154), or percentage correct (r (30)=-.212,p=. 261).

Table 2 here

4.2 Is metacognitive sensitivity across process domains related?

Analysis revealed that metacognitive efficiency for perceptual decisions (A_{roc}) and memorial judgments (M_{Ratio}) were uncorrelated across individuals (*r* (30)= .134,p=. 471), indicating an intraindividual dissociation in metacognitive ability across process domains. To ensure that this result was not an artifact of the fact that metacognitive ability for memory and perception were in different units (M_{Ratio} and A_{roc}), M_{Ratio} was also calculated for the perception task and correlated with M_{Ratio} for the memory recognition task. These measures were uncorrelated across individuals (*r* (30)=. 096, *p*=. 607), indicating that the lack of correlation between perceptual and memorial metacognitive ability cannot be attributed to differences in the scale between M_{Ratio} and A_{roc}.

Figure 3 here

Further, considerable variation was observed (figure 4) across individuals in both the Memory task (M_{Ratio}= .36- 1.86, M= .85) and Perception task (M_{Ratio}= .06 - 1.04, M= .64) demonstrating that these tasks are sensitive to a broad range of metacognitive ability in this sample and the absence of relationship between these domains is unlikely due to uniformity of metacognition in a neurotypical population. Moreover, for the memory task, both proportion correct (Pearsons *r* = -.118 *P*= .535) and d' (Pearsons *r* = -.241 *P*=. 200) were uncorrelated with M-Ratio. In a similar vein, on the perceptual task, both proportion correct (Pearsons *r* =-.150 *P*=. 429) and d' (Pearsons *r* =-.171 *P*=. 366) were also uncorrelated with M-Ratio.

Figure 4 here

4.3 Is metacognitive ability related to awareness of error?

No significant relationship emerged between awareness of error and M_{ratio} (Pearson's r =. 131, p=. 490) or $M_{difference}$ (Pearsons r =. 114, p=. 549) for the perceptual task or M_{ratio} (Pearsons r =-.145, p=.445) or $M_{difference}$ (Pearsons r = -.077 p=.685) for the memorial task.

In addition, error awareness was also not correlated with area under the curve for the perceptual (Pearsons r =. 160, p=. 398), or memorial task (Pearsons r =-.212, p=. 261).

In case the relationship between M_{ratio} on the Perceptual or memorial tasks and error awareness on the EAT was specific to identifying obvious errors using the confidence scale, we also looked at trials with low confidence ratings (confidence rating 1 or 2). Confidence ratings of 1 or 2 are the closest equivalent to a discrete error response in the RCJ tasks. We checked whether the proportion of objective error versus correct at this confidence level (a proxy of "error awareness") related to error awareness in the EAT. No significant relationships were observed between error awareness on the EAT task and incorrect (Pearsons r =-.123., p=.518) or correct trials (Pearsons r =-.056., p=.769) rated with a confidence of 1 on the perpetual task. Moreover, no significant relationships were observed between error awareness on the EAT task and incorrect (Pearsons r =. 038, p=. 840) or correct trials (Pearsons r =. 154, p=. 417) rated with a confidence of 1 on the memorial task.

Differences in task characteristics, specifically the graded reporting of confidence versus the binary reporting of errors, could account for the absence of a relationship between these domains. As such, it is important to know if the confidence judgments are equally sensitive to erroneous decisions and correct decisions. To this end, the degree to which subjective confidence in both the perceptual and memory tasks was predictive of objective accuracy (i.e., the degree of calibration) was investigated (see Figure 5). Following perceptual decisions, participants were more confident (on the 6-point scale) for trials with correct responses (M=4.69,SD=. 96) than for error trials (M=3.93,SD=1.02, $t(29)=7.97$, $p<.001$). In a similar vein, participants were more confident making memorial decisions on correct trials (M=4.99,SD=. 48) compared to confidence on error trials (M=3.98, SD= .77, t (29)=9.77, p<. 001). Participants made perceptual errors on 59.02% of trials judged "not confident" compared with an error rate of 8.89% of trials judged "very confident". Participants made memorial errors on 60% of trials judged "not confident" compared with an error rate of 6.56% of trials judged "very confident". In addition, each participants meta-d' was checked to ensure that it was reliably above zero to ensure that the calibration analysis was accurate. Subjective confidence in both the memory and perceptual decision making tasks are therefore calibrated with objective performance.

Figure 5 here

4.4 Relationship between Response Times and Metacognitive Ability

Of interest were potential interrelationships between the second-order (type-2) response times for confidence and error awareness. Greater mean RT for the awareness response on the EAT was associated with increased mean RT confidence judgments following incorrect trials on the perceptual task (r=. 364, p=. 048) and following both correct (r=. 377, p=. 040) and incorrect (r=. 554, p=. 001) trials on the memory task. . No significant relationship emerged between the Type 2 mean RT on the decision confidence tasks and the Type 1 mean RT for unaware errors on the EAT.

4.5 Does self-reports of daily functioning differ from informant reports of daily functioning?

On average, the participants reported significantly fewer difficulties with attentional control on the CFQ (M=1.0, SD=. 65) relative to their informants (M=1.49, SD=. 53; t (58)=-2.93,p=. 005).

The participants also reported fewer memory functioning difficulties on the MFQ (M=37.31, SD=11.11) relative to their informants (M=38.43, SD=9.33). However, this difference was not significant t (57)=-.421, p>.05.

4.6 Is online metacognition related to reports of daily functioning?

To investigate whether informant reports of daily functioning correspond with online metacognitive accuracy, relationships between the CFQ and MFQ, ratings and participants' meta-d' ratings on the perceptual and memorial decision confidence tasks were examined (see table 3). There was a significant positive relationship between participants' perceptual m-ratio and informants' ratings on the CFQ (r=. 464, p=. 010) indicating that participants with higher levels of metacognitive capacities (as measured by how well meta-d' and d' calibrate) were perceived by their informants to have fewer problems with attentional control in everyday life. Significant positive relationships were also observed between the perceptual decision-making M-Difference and informant CFQ (r=. 403,p=. 027). There were no other significant relationships between self or informant reports and online metacognitive measures (all p > .05).

Table 3 here

In order to investigate the relationship between metacognitive ability and awareness in daily life, discrepancy measures were calculated for self minus informant reports on the CFQ and MFS. The associations between these discrepancy scores and participants metacognitive performance on the memory, perceptual and error awareness task was then examined. M-ratio on the perceptual task was significantly correlated with CFQ-D (r=. 407,p=. 026). A significant relationship emerged between the CFQ-D and area under the curve, Aroc, in the perceptual task (r=. 501, p=. 005) indicating that individuals who demonstrated higher metacognitive ability on the perceptual task were reported to be more competent on reports of daily functioning by their informant.. There were no further significant relationships between the metacognitive awareness tasks and discrepancy measures of awareness in everyday life (all p > .05)

Table 4 here

4.7 Relationship between metacognitive ability, detection of errors and standardized test performance

There was no observed correlation between estimated premorbid IQ (National Adult Reading Test; NART) FSIQ scores and metacognitive accuracy on the perceptual task (*r* =-

.103,p=. 59), memory task (*r*=-.235,p=. 21) or awareness of errors on the EAT (*r* =. 29, p=. 12) across all subjects, consistent with an absence of a relationship between IQ and metacognition observed in previous studies of healthy individuals (Weil et al., 2013) and individuals who have sustained a brain injury (Fleming, Ryu, Golfinos & Blackmon, 2014). However, on tests of neuropsychological performance, there was a significant negative correlation between participants M-ratio on the memory test and performance on the RBANS total scale score (r=-.366, p=. 047).

5.0 Discussion

This investigation provides further evidence that metacognition is not a domain general capacity but rather is instantiated differently across three cognitive domains. Specifically, we found that metacognitive accuracy for perceptual decision confidence, recognition memory confidence and awareness of action errors was dissociable. This finding is consistent with recent neuropsychological evidence that suggests metacognition is supported by domain-specific components.

Fleming et al. (2014) measured metacognitive accuracy in patients with lesions to aPFC in two distinct domains, perception and memory, by assessing the correspondence between objective performance and subjective ratings of performance. Despite performing equivalently to brain-damaged and healthy controls, patients with lesions to the aPFC showed a selective deficit in perceptual metacognitive accuracy. Crucially, however, the aPFC group's metacognitive accuracy on a directly equivalent memory task remained unimpaired. One alternative reason for this single dissociation, acknowledged by Fleming and colleagues may be due to differences in the stimulus characteristics of the memory task (verbal stimuli) and perceptual task (visuospatial dot stimuli) raising the possibility that metacognitive accuracy may be influenced by local properties of each task.

Importantly, in the current study, each of the three tasks utilized the same set of verbal stimuli, controlling for the material subjected to metacognitive evaluation, therefore the domain dissociation cannot be explained by differences in stimuli across the tasks. The results of the present study, therefore, lend support to the possibility of distinct metacognitive mechanisms for different kinds of metacognition, and that each cognitive process may be monitored by its own metacognitive system, as proposed by Nelson & Narens (1990) and Shimamura (2000), Indeed, the current evidence of domain specific processes is consistent with both functional connectivity results (Baird et al., 2013) and voxel-based morphometry findings (McCurdy et al., 2013), which report distinct neuroanatomical substrate for dissociable metacognitive systems that rely on different subregions of aPFC and medial parietal cortex.

In this study we have also endeavored to show that metacognitive ability could not simply be accounted for by variation in objective performance. Accuracy did not differ across the three tasks and was dealt with in two ways: by using adaptive staircase procedures to control for difficulty levels (in the perceptual and error awareness tasks) and by calculating meta-d'/d' (in the perceptual and memory tasks), which captures metacognitive efficiency unadulterated by variance in primary task performance. We also note that our sample contains high variance in metacognitive ability for participants across all three tasks indicating that there was sufficient between-subject variance in metacognitive accuracy so not to preclude detection of domain general relationships should they have been present. Thus, our tasks elicited a broad range of metacognitive ability that was neither at ceiling nor floor, while controlling for differences in objective performance.

Although our findings suggest domain specificity in metacognitive accuracy, we found that second-order mean RT for confidence judgments was associated with second-order mean RT for awareness of errors, This relationship suggests that, at least for the tasks studied, there are shared post-decisional processes across all domains that are dynamic, temporally extended processes that may accrue evidence concerning the veracity of a decision. These results support Yeung and Summerfield's (2012) proposal that common mechanisms or a shared reliance on post-decisional processing may govern metacognitive judgments of confidence and error monitoring. Indeed, Boldt and Yeung (2015) have found shared neural markers of error detection and decision confidence. In an electroencephalographic (EEG) study assessing confidence judgments during a dot count perceptual decision task, they found that the error positivity (Pe) – an event related component which has been shown to build in amplitude to the point of an error awareness response (Murphy et al., 2012) – also systematically increases in amplitude with diminishing confidence of one's prior decision choice. These findings suggest, at least in the context of a single perceptual decision task, that the Pe is not only a marker for error awareness but scales with graded changes in decision confidence. It remains to be seen if the Pe is a supramodal signal that indexes a common process across multiple domains of decision-making. Our findings from this study suggest that there may be some common processes reflected in correlated metacognitive decision times and the timing of error awareness signaling. However, if metacognitive accuracy is dissociable across domains, then this implies that the evaluation of different sources of evidence might require more specialized domain dedicated processors that are not supramodal.

One theory that allows for subjective awareness to be realized across different cognitive domains is the Attention Schema Theory (Graziano & Webb, 2015). An attention schema is conceived as a top-down internal model of the current focus of attention. Constructing a model of attention enables the brain to determine that it has subjective awareness. Given that attention can be flexibly deployed across multiple domains, an attention schema, by virtue of it representing the process of attention, will also track multiple types of information. The theory also allows for a dissociation between subjective awareness and attention, which helps explain why neuropsychological patients can show accurate attentional performance but at the same time hold an imperfect model of this process (Fleming et al., 2014).

There has been little research investigating the relationship between online laboratory measures of metacognition and reports of cognitive function in daily life. The current study provides evidence that observational reports of cognitive failures in daily functioning (by a close informant) can predict online metacognitive accuracy on a perceptual task. By contrast, participants' self-reports of daily functioning and their online metacognitive accuracy did not correlate. Pronin (2008) suggests that one possible explanation for an informant's ability to assess an individual in objective terms maybe because the individuals themselves have a tendency to perceive themselves via "introspection" (looking inwards to thoughts, feelings, and intentions) and others via "extrospection" (looking outwards to observable behavior). Importantly, this relationship with informant ratings of observable behavior suggest that assessing metacognitive ability in the laboratory can provide a useful analogue of daily life performance.

Further, diminished awareness in individuals who under-reported attentional lapses and memory failures in daily life relative to informant reports was also predictive of metacognitive ability in the perceptual domain. Reduced awareness of performance on this simple experimental measure was associated with less awareness of cognitive failures in daily life within the normal continuum of metacognitive ability. This finding is novel in that under-reporting of daily cognitive failures and their relationship to laboratory measures of metacognition has only been seen in older adults (Harty et al., 2013) or patients with brain damage (Dockree et al., 2015).

An important benefit of assessing objective metacognitive performance is its predictive utility. Recent evidence suggests that awareness of memory impairment begins to decline 2-3 years before the onset of dementia (Wilson et al. 2015). There is also evidence that reduced efficiency of sustained attention – an important allied process to awareness (Robertson, 2014) - is a reliable predictor of falls in older adults (O'Halloran et al 2011). Furthermore, the breakdown of top-down control and resultant executive dysfunction has been shown to predict gait impairment and retrospective falls in Alzheimer's patients (Sheridan & Hausdorff, 2007. Given these associations in the literature, it is possible that indices of awareness could be important pre-clinical markers of decline across different domains. For example, McGlynn & Kaszniak (1991) identified self-awareness deficits such as the under reporting difficulties with activities of daily life, as an important predictor of dementia severity. Self-awareness has also been found to be an important predictor of outcome for brain injury patients. O'Keeffe and colleagues (2007) found a strong relationship between executive dysfunction abilities and overall metacognitive knowledge following brain injury. Patients with low self awareness demonstrated poorer behavioural outcome and neuropsychological profiles compared to high self awareness patients. From a clinical perspective, metacognitive self-awareness is of considerable importance in brain rehabilitation since a lack of acknowledgement of problems mitigates against taking the necessary steps to overcome difficulties. Accurate, objective measures of metacognitive awareness are required.

Finally, we examined relationships between metacognitve accuracy and standardised measures of cognitive function. Consistent with previous research (Fleming, Huijgen & Dolan, 2012) we found no relationship between metacognitive ability and an index of general intellectual function. However, a significant relationship between online metacognitive awareness in the memory domain and overall cognitive performance, as measured by the RBANS total scale index, was apparent. The implications of this relationship is that metacognitive ability, at least in the memory domain, may depend on a broad array of cognitive processes captured in the total scale index, rather than specific cognitive domains measured by any one of the five index scores from each of the RBANS subtests. Our findings highlight the multidimensional nature of metacognition and self-awareness and is consistent with the mixed finding in clinical research that has found it difficult to establish reliable and distinct neuropsychological profiles for clinical patients with impaired and intact awareness. For example, although some investigations have demonstrated a positive relationship between poor performance on standard neuropsychological tests and impaired self awareness in TBI groups (Anderson & Tranel, 1989) others have not (O'Keeffe et al., 2007). It is possible that studies have produced inconsistent results given the wide variety of subjective methodologies implemented in studying self awareness (Consentino & Stern, 2005).

We also acknowledge some limitations in experimental design that prevented us from exploring several important issues. For our decision confidence tasks, we focused on post-trial confidence as our measure of metacognition. Others have investigated other forms of metacognition that involve prospective judgments, such as feeling of knowing (Souchay et al., 2006) and judgment of learning (Nelson and Dunlosky, 1991). At least in the memory domain, it is known that some aspects of prospective and retrospective metacognitive judgments may depend on dissociable neural substrates to some extent (Pannu, Kaszniak & Rapcsak, 2005; but see Choa, Schacter and Sperling, 2009). Therefore, the interpretation of the present results is restricted to the relationship between error-monitoring and post-trial confidence-based metacognition and may not generalize to prospective metacognitive judgments.

6.0 Conclusions

In conclusion, a behavioural dissociation was observed across different types of metacognitive evaluations and awareness as revealed by converging results across measures of online error awareness and measures of decision confidence in perception and memory domains. This is consistent with emerging functional neuroimaging evidence and is also in accord with the observations of lesion-based analysis research that investigated the causal manipulation of metacognition. The findings of this study lend support to previous research that suggest that metacognition and awareness may be underpinned by domain specific mechanisms. Investigating the broader implications of domain-specific metacognitive awareness in order to understand the breakdown in awareness following brain injury is an important pursuit for future research.

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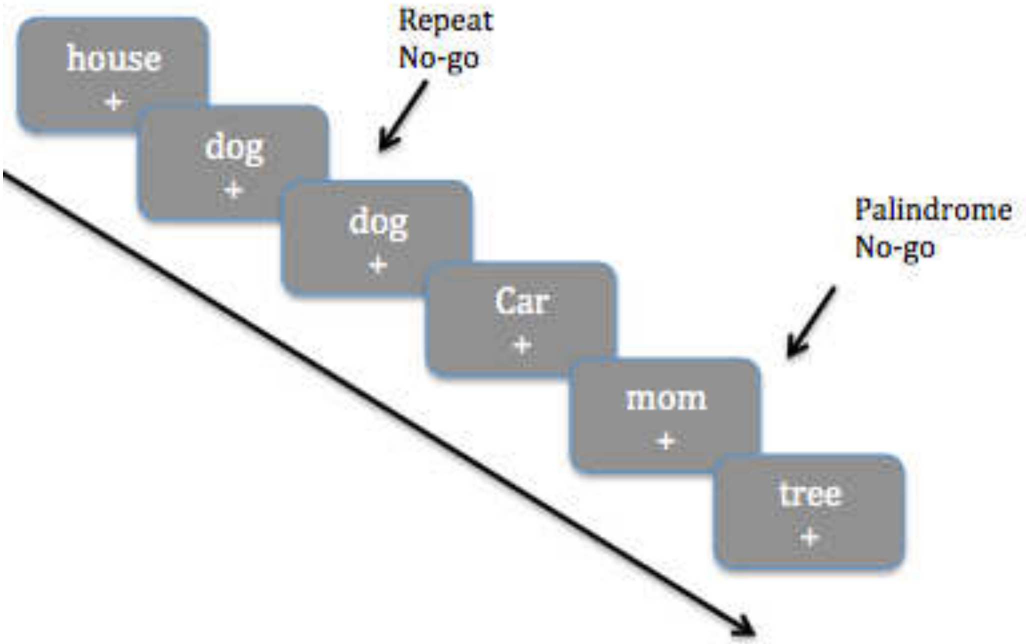


Figure 1: Schematic of a modified version of the Error Awareness task used to examine error monitoring. Participants were required to make a speeded button press ("A") when a word appears on screen and to withhold from responding to words that would be classified as a palindrome (Palindrome no-go) or when a word was repeated on consecutive trials (Repeat no-go). In instances where participants failed to correctly withhold to a response, they were required to press a separate button ("B") to signal error awareness.

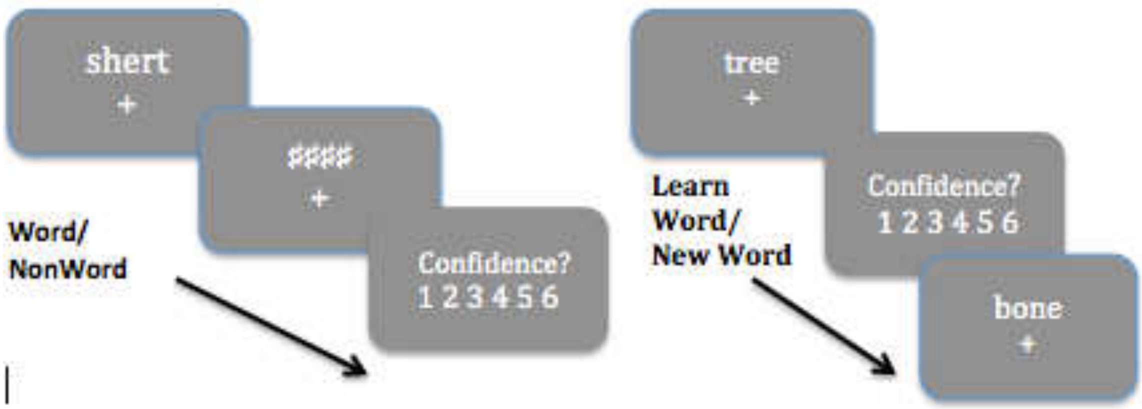


Figure 2: Post Decisional Confidence tasks**. A.** Perceptual Decision Task. Participants were required to detect whether a masked stimulus was a word or a nonword and then indicate their confidence in accuracy. **B.** Memory retrieval task. The memory task consisted of a classic verbal recognition memory paradigm. During encoding, participants viewed a word list containing 60 words.

During recognition, participants were presented with each word from the full list of 120 stimuli in a random order (half of which were presented during encoding and half of which were new) and were asked to make discrimination judgments as to whether the stimulus was old or new, and then subsequently rated their confidence in their response.

Table 1 Comparison of performance indices in the perception, memory and error awareness tasks: Means and (SD).

Task		**Average Group Performance** (*n*=30)
Memory	Type 1 performance Accuracy (%)	80.58 (7.92)
	Confidence	4.73 (.53)
	Meta d'/d' (MRatio)	.85 (.38)
Perception	Type 1 performance Accuracy (%)	83.00 (8.27)
	Confidence	4.51 (.96)
	Meta d'/d' (MRatio)	.64 (.24)
Error Awareness	Type 1 performance Accuracy (%)	77.20 (12.03)
	Error Awareness (%)	86.14 (19.09)

Table 2: Mean errors of commission and mean error awareness proportion scores on the EAT for neurologically healthy control participants

	Mean (SD)	Median	Range	Min-Max
% Error Awareness	86.14 (19.09)	100	71.43	28.57-100
% Withholding on no-go trials accuracy	73.03 (13.77)	76.19	52.38	38.10-90.48
Mean unaware errors of Commission	.97 (1.38)	0	5	0-5
Mean aware errors of commission	4.27 (1.82)	4	6	2-8
Mean Palindrome error of Commission	2.57 (1.17)	2	5	0-5
Mean Repeat error of commission	2.67 (1.83)	2	7	0-7
Mean Palindrome aware error of commission	2.27 (1.26)	2	5	0-5
Mean Repeat aware error of Commission	2.00 (1.26)	2	5	0-5
Mean Palindrome unaware error of Commission	.30 (.65)	0	2	0-2
Mean Repeat unaware error of commission	.67 (1.06)	0	3	0-3

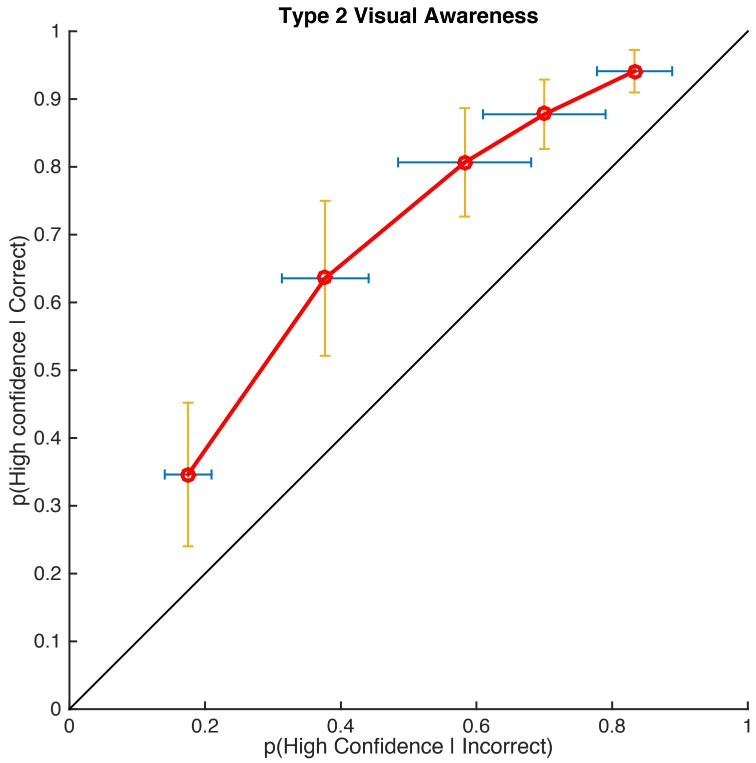


Figure 3: Type 2 ROC analysis. Type 2 ROC curves were estimated for each subject using estimates of meta-*d';* the average of these ROC curves is plotted for the perceptual (red line) domain. Type 2 Roc Curves were constructed for each participant on the perceptual task that characterized the probability of being correct for a given level of confidence. Type 2 Receiver Operating Characteristic (ROC) Curves reflect the relationship between the accuracy of discriminations and the observer's confidence rating. Note that Controlling for type 1 performance by experimental design in a recognition memory paradigm is methodologically difficult therefore quantification of metacognitive accuracy in the memory task required a computational approach meta-d'/d' that explicitly accounts for type 1 performance.

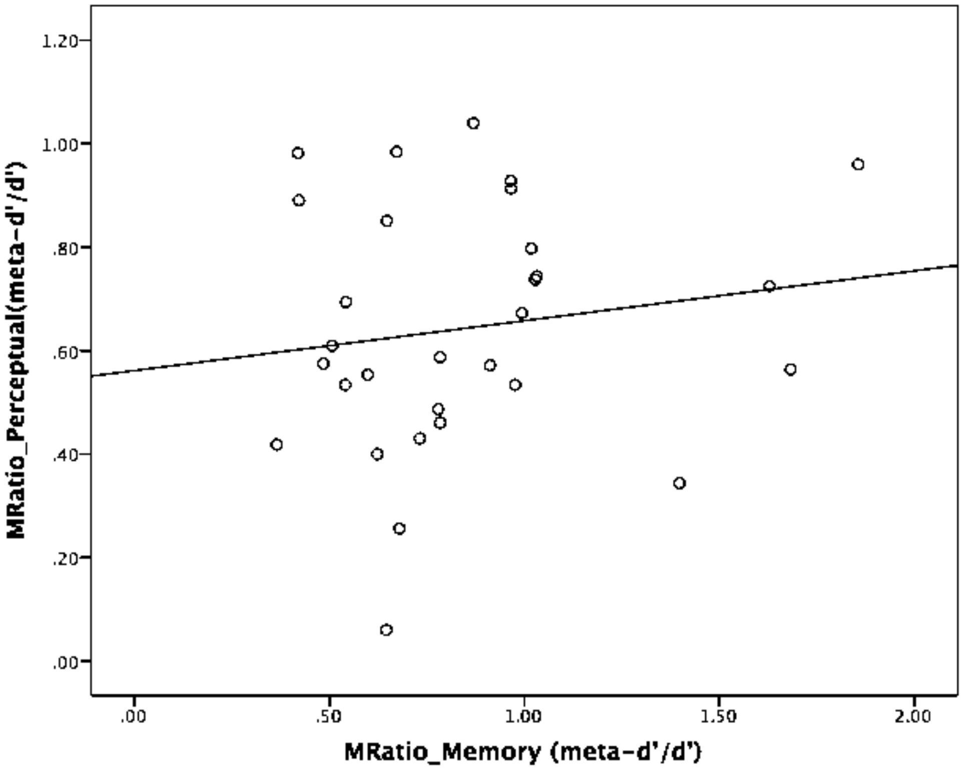
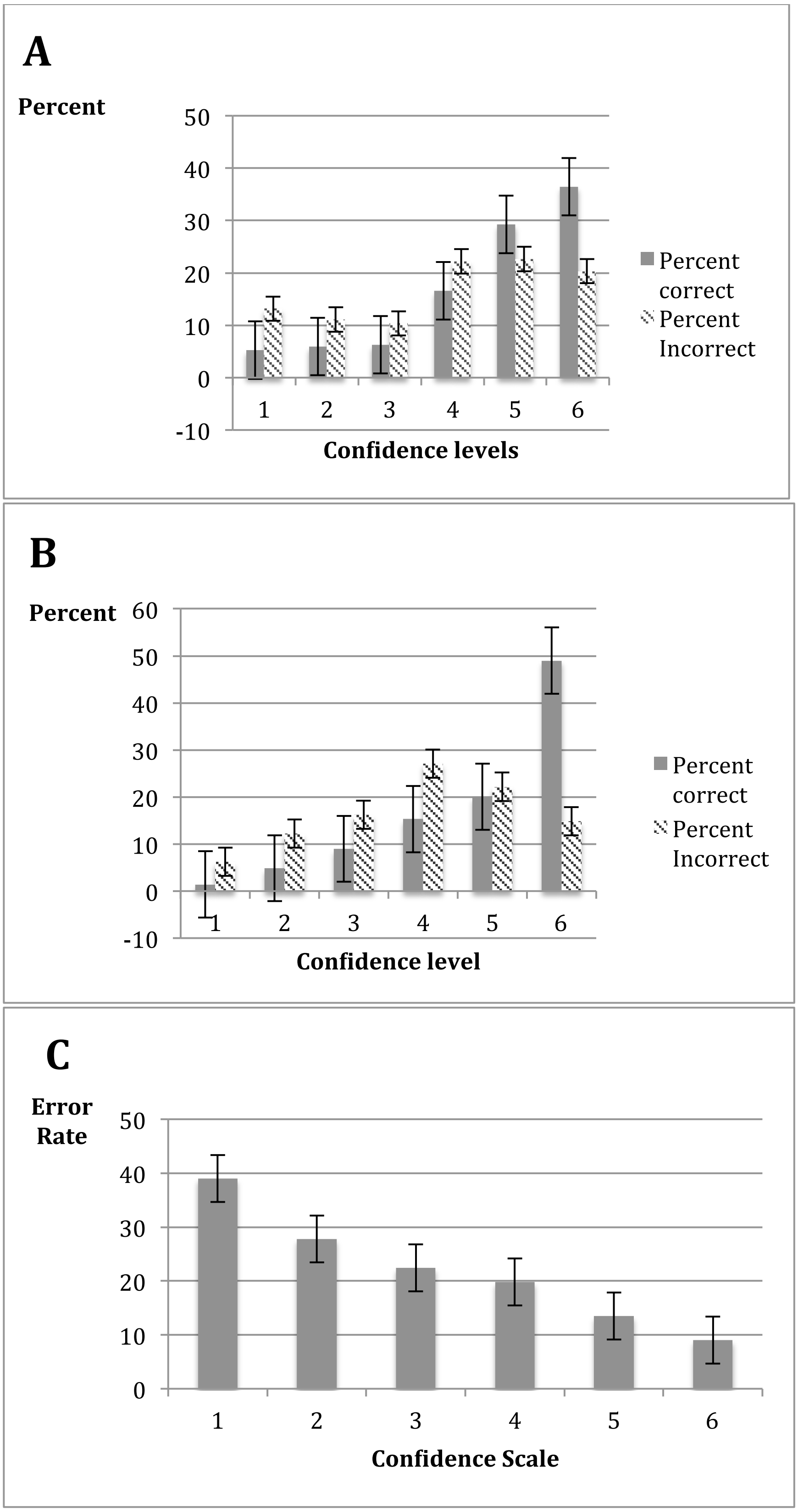


Figure 4. Scatter plot demonstrating zero-order correlation between metacognitive efficiencies in the perceptual and memory tasks. [r=(30)=.096,*p*=.607]. Considerable variation was observed across individuals in both the Memory and Perception task demonstrating that these tasks are sensitive to a broad range of metacognitive ability in this sample and the absence of relationship between these domains is unlikely due to uniformity of metacognition in a neurotypical population.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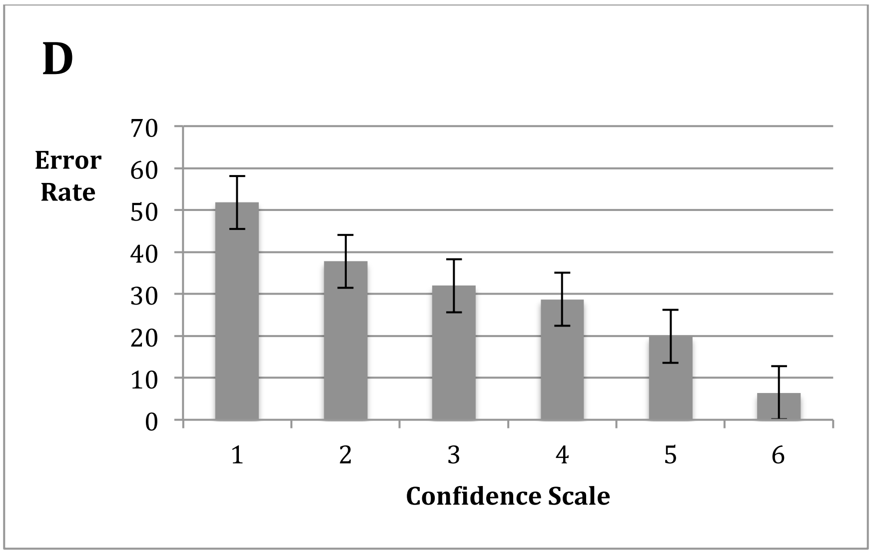

Figure 5.***A,*** Distribution of confidence levels as a function of objective accuracy on the perceptual decision task. ***B,*** Distribution of confidence levels as a function of objective accuracy on the memory task. ***C,*** Distribution of confidence levels as a function of objective accuracy on the perceptual decision task. ***D,*** Objective accuracy as a function of subjective confidence on the memory task. Error bars indicate within-subject confidence intervals.

Table 3: Pearson correlation coefficients for online metacognitive performance and the self-awareness in daily life discrepancy questionnaires

Measure	1.	2.	3.	4.	5.
1.PD A^{ROC}					
2.PD $M_{Difference}$	**.524****				
3.PD M_{Ratio}	**.690****	**.891****			
4. CFQ $_{Self}$	**-.095**	**.190**	**.145**		
5.CFQ $_{Informant}$	**.297**	**.403***	**.464****	**.396***	
6.CFQ-D	**.472****	**.381***	**.444***	**.698****	**.261**

PD AROC, Perceptual Decision area under the curve; PD MDifference, Perceptual decision task MDifference; PD Mratio, Perceptual Decision Mratio; CFQ Self, Cognitive Failures Questionnaire self report; CFQ Informant, Cognitive Failures Questionnaire informant report; CFQ-D, Cognitive Failures Questionnaire-Discrepancy.

*p value > .05

**p value > .01

Table 4: Questionnaire measures of awareness. Mean (SD) self-ratings, informant ratings and corrected discrepancy scores on the CFQ and MFS,.

	Min-Max	Mean (SD)	Range
CFQ Self Average	.32-2.76	1.0 (.65)	2.44
CFQ Informant Average	.00-2.88	1.49 (.53)	2.88
MFS Self	13-49	38.43 (9.33)	36
MFS Informant	11-52	37.31 (11.11)	41
Corrected Discrepancy Scores			
CFQ-D		-1.26(.42)	1.87
MFD-D		.06 (.30)	1.60

CFQ, Cognitive Failures Questionnaire; MFS, Memory Functioning Scale; CFQ-D, Cognitive Failures Questionnaire Discrepancy score; MFD-D, Memory Functioning Scale Discrepancy score.

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