Chapter 12
The Cognitive Neuroscience of Metamemory Monitoring: Understanding Metamemory Processes, Subjective Levels Expressed, and Metacognitive Accuracy

Elizabeth F. Chua, Denise Pergolizzi and R. Rachel Weintraub

Abstract Metamemory has been broadly defined as knowledge of one's own memory. Based on a theoretical framework developed by Nelson and Narens (Psychol Learn Motiv 26:125–141, 1990), there has been a wealth of cognitive research that provides insight into how we make judgments about our memory. More recently, there has been a growing interest in understanding the neural mechanisms supporting metamemory monitoring judgments. In this chapter, we propose that a fuller understanding of the neural basis of metamemory monitoring involves examining which brain regions: (1) are involved in the process of engaging in a metamemory monitoring task, (2) modulate based on the subjective level of the metamemory judgment expressed, and (3) are sensitive to the accuracy of the metamemory judgment (i.e., when the subjective judgment is congruent with objective memory performance). Lastly, it is critical to understand how brain activation changes when metamemory judgments are based on different sources of information. Our review of the literature shows that, although we have begun to address the brain mechanisms supporting metamemory judgments, there are still many unanswered questions. The area with the most growth, however, is in understanding how patterns of activation are changed when metamemory judgments are based on different kinds of information.

E. F. Chua (✉) · D. Pergolizzi · R. R. Weintraub
Department of Psychology, Brooklyn College of the City University of New York,
2900 Bedford Ave, Brooklyn, NY 11210, USA
e-mail: echua@brooklyn.cuny.edu

D. Pergolizzi
e-mail: dpergolizzi@brooklyn.cuny.edu

R. R. Weintraub
e-mail: rweintraub@brooklyn.cuny.edu

E. F. Chua · D. Pergolizzi · R. R. Weintraub
Department of Psychology, The Graduate Center of the City University of New York,
365 5th Ave, New York, NY 10016, USA

S. M. Fleming and C. D. Frith (eds.), *The Cognitive Neuroscience of Metacognition*,
DOI: 10.1007/978-3-642-45190-4_12,

12.1 Introduction

Metamemory can be broadly defined as knowledge of one's own memory [58]. Research on metamemory has a long history in cognitive psychology, but in the past decade there has been a growing interest in understanding the neural mechanisms associated with metamemory (e.g., [16–19, 34, 45, 49, 51]). It has everyday relevance for patients with neurological and psychiatric disorders, and even the healthy aged, who have deficits in metamemory (e.g., [6, 60, 86]), for educators who want to promote learning (e.g., [48, 89]), for basic researchers interested in the fundamental computations carried out by specific brain areas and how they interact [16–19, 34, 50], and for people who swear they left their keys by the door only to find them in the kitchen. The goal of this chapter is to review the current literature on the cognitive neuroscience of metamemory monitoring, and to provide guidelines for future neuroimaging studies investigating metamemory.

12.1.1 Theoretical Framework of Metamemory: A Brief Overview

The guiding framework for studying metamemory is the Nelson and Narens [58] model that defined metamemory as the combination of *monitoring* and *control* processes (Fig. 12.1). Monitoring involves judging the success and/or progress of memory processing, and can be studied by asking for subjective introspections. Different kinds of monitoring occur during different stages of memory (e.g., encoding and retrieval), and thus there are several different tasks that ask for subjective reports at these different stages. The control component is the action-oriented component, which allows individuals to direct their behavior, typically by selecting information, choosing strategies, or ending processes. Extensive behavioral research has examined both monitoring and control processes, but the majority of research on the cognitive neuroscience of metamemory has focused on monitoring processes, which will be our main focus.

12.1.2 Metamemory Monitoring Tasks

Many tasks have been devised to probe metamemory monitoring at different stages during mnemonic processing ([58]; Fig.12.1). This can be done at a *global* level by asking people to make overall judgments about their memory performance (e.g., how many questions do you think you will get correct on the memory test that you will take shortly?), or at a trial-by-trial level by asking people to make a judgment after each trial. Judgments of learning (JOLs) are predictive judgments that are taken during, or shortly after, the study phase, and ask participants to judge how

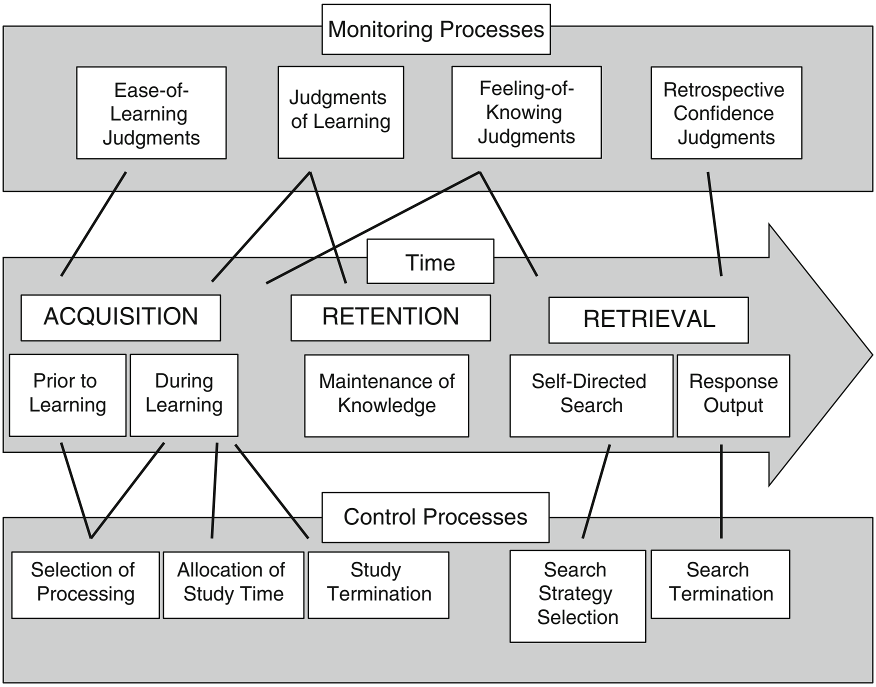

Fig. 12.1 The theoretical framework of monitoring and control processes in metamemory. Adapted with permission from Nelson and Narens [58]

likely they will later remember information. Feeling-of-knowing (FOK) judgments are taken during the retrieval phase and occur after a failed attempt at recall, and require participants to indicate how likely they are to recognize the information later. A related phenomenon is the Tip-of-the-Tongue (TOT) state, which has been distinguished based on its subjective feeling of imminent retrieval and accompanying frustration. On the postdictive side are retrospective confidence judgments (RCJs), which are made after recall or recognition and ask participants to indicate how certain they are that their responses are correct.

12.1.3 Measuring Metamemory Accuracy

Metamemory tasks require individuals to introspect about the contents of their mind and then make a subjective report (for review, see [3]). To get a measure of metamemory accuracy the discrepancy between the subjective reports and the objective results of the memory tests are compared (for review, see [7]). Broadly speaking, there are two main types of measurement, *absolute* and *relative* measures. Absolute measures, such as calibration curves and the Hamann index, are tied to the subjective rating scale used in the metamemory task and examine how well the subjective measures reflect performance on the memory task. However, people may use the scale differently, and may not be well calibrated, yet their performance does get better as their ratings increase, which shows a degree of metamemory accuracy in that there is some correlation between subjective ratings and objective performance. This is where *relative* measures of metamemory are important, and the most commonly used measure is the Goodman–Kruskal Gamma, a measures of association based on the difference between concordant and discordant pairs. More extensive reviews of measures of metamemory accuracy are reviewed elsewhere ([7, 60, 87]; Fleming and Dolan, this volume), and are beyond the scope of this chapter.

12.1.4 Tackling the Cognitive Neuroscience of Metamemory

Neuroimaging allows us to compare brain activity in many ways. We believe that this can bring us to a better understanding of the many facets of metamemory, and that it is necessary to understand: (1) brain regions that are involved in engaging *metamemory processes*, (2) brain regions that modulate based on the subjective *level* of the judgment expressed (e.g., high compared to low confidence), and (3) regions that correlate with *metamemory accuracy*, in which the subjective judgment and memory outcome are congruent (Table 12.1). Understanding the way the brain contributes to these three aspects of making metamemory judgments is fundamental in our attempts to understand metamemory and the brain. There is still much work to be done in understanding these three aspects across the different metamemory tasks. Once these basics are understood, the critical next steps are then to understand how these activations may change when metamemory decisions are based on different kinds of information (e.g., episodic vs. semantic, experiential vs. inferential). Although neuroimaging research at that level of specificity is currently rare, there are a few studies that meet this goal (e.g., [74, 85]). Finally, we will also examine common and distinct aspects of metamemory across tasks. Neuroimaging is correlational, so it is also necessary to examine metamemory in patients with brain lesions to determine if these brain regions are necessary for metamemory (Table 12.2), or to use brain stimulation techniques such as transcranial magnetic stimulation (TMS) or transcranial direct current stimulation (tDCS). Similar to their temporal order, we will begin with JOLs and end with RCJs.

12.2 Judgments of Learning

JOLs occur during or after learning, and are defined as predictions made about the ability to later retrieve information that is currently recallable [58]. In most JOL paradigms, participants study information and then give a subjective rating on how

Table 12.1 Brain regions associated with different aspects of metamemory using fMRI

Study	Judgment	Brain regions
Regions engaged in the processes of metamemory monitoring		
Do Lam et al. [45]	JOL	mPFC; OFC
Chua et al. [19]	FOK	vmPFC; DLPFC; PCC; lateral PPC; MTL
Chua et al. [17]	RCJ	DLPFC; precuneus; ventral PPC
Chua et al. [19]	RCJ	vmPFC; DLPFC; VLPFC; PCC; lateral PPC
Regions modulating by the subjective level of the judgment expressed		
Kao et al. [34]	JOL	VLPFC; vmPFC; amygdala; precuneus; lateral temporal; occipital cortex
Do Lam et al. [45]	JOL	mPFC; OFC; ACC
Chua et al. [19]	FOK	MTL; PCC; superior temporal; fusiform
Elman et al. [22]	FOK	VLPFC; DLPFC; mPFC; ventral PPC; PCC
Jing et al. [32]	FOK	DLPFC
Kikyo et al. [37]	FOK	VLPFC; DLPFC
Kikyo and Miyashita [36]	FOK	mPFC; aPFC; VLPFC; DLPFC; anterior temporal; lateral PPC
Maril et al. [49]	FOK	DLPFC; ACC; dorsal PPC
Maril et al. [50]	FOK	Medial and lateral parietal cortex
Schnyer et al. [74]	FOK	Medial and lateral PFC; PCC; MTL
Kikyo et al. [38]	TOT	DLPFC; ACC
Maril et al. [51]	TOT	mPFC; VLPFC; ACC; lateral temporal
Maril et al. [50]	TOT	aPFC; DLPFC; VLPFC; ACC
Chua et al. [17]	RCJ	mPFC; insula; PCC; MTL
Chua et al. [18]	RCJ	Lateral PFC; mPFC; ACC; MTL; PCC; lateral PPC
Hayes et al. [26]	RCJ	VLPFC; MTL; dorsal PPC
Henson et al. [28]	RCJ	DLPFC
Kim and Cabeza [39]	RCJ	Lateral PFC; PCC; Lateral PPC
Moritz et al. [56]	RCJ	ACC; PCC; MTL; dorsal PPC
Regions modulating by metamemory accuracy		
Kao et al. [34]	JOL	vmPFC
Schnyer et al. [74]	FOK	VLPFC; vmPFC; ACC; MTL
Yokoyama et al. [94]	RCJ	Fronto-polar cortex

Note JOL judgments of learning, *FOK* feeling-of-knowing, *RCJ* retrospective confidence judgments, *mPFC* medial prefrontal cortex, *OFC* orbitofrontal cortex, *DLPFC* dorsolateral prefrontal cortex, *VLPFC* ventrolateral prefrontal cortex, *vmPFC* ventromedial prefrontal cortex, *ACC* anterior cingulate cortex, *PPC* posterior parietal cortex, *PCC* posterior cingulated cortex, *aPFC* anterior prefrontal cortex

likely they think they are to recall the information later. These subjective ratings may be given immediately or after a delay. Typically, delayed JOLs are more accurate than immediate JOLs, which indicates that they may be based on different sources of information [57]. Immediate JOLs are thought to be based on monitoring working memory, whereas delayed JOLs are thought to be based on monitoring long-term memory [58].

Table 12.2 Neuropsychology of metamemory

Study	Lesion group	Comparison group	Spared	Impaired
Vilkki et al. [90]	R frontal	Controls		Word list recall; global JOLs
	R frontal	Posterior lesion	Word list recall	Global JOLs
	L frontal	Control		Word list recall; global JOLs
	L frontal	Posterior lesion	Global JOLs	Word list recall
Vilkki et al. [91]	R frontal	Controls	Face-location learning	Global JOL
	R frontal	Posterior lesions	Face-location learning	Global JOL
	L frontal	Controls	Face-location learning; global JOL	
	L Frontal	Posterior lesions	Face-location learning; global JOL	
Andres et al. [1]	TLE	Controls	Item JOL	Recall; recognition
Howard et al. [30]	TLE	Controls	Item JOL	Recall; recognition
Howard et al. [29]	TLE	Controls	Global and item JOLs	Recall; recognition
Bastin et al. [6]	FTD	Controls		Recall; recognition; FOK
Modirrousta and Fellows [55]	mPFC	Controls	JOL; RCJ	FOK
Pannu et al. [61]	Frontal	Controls	Recognition; FOK	RCJ
Perrotin et al. [62]	MCI	Controls	Commission errors (recall)	Omission errors (recall); FOK
Schmitter-Edgecombe and Anderson [73]	CHI	Controls	RCJ	Recall; recognition; FOK
Schnyer et al. [75]	Frontal	Controls	RCJ	Recall; recognition; FOK
Souchay et al. [86]	Older adults	Young controls	Semantic FOK	Recall; episodic FOK
Davidson et al. [21]	Parietal	Controls	Recognition	Recollection; RCJ
Simons et al. [83]	Parietal	Controls	Recognition	Recollection; RCJ

Note JOL judgments of learning, *FOK* feeling-of-knowing, *RCJ* retrospective confidence judgments, *TLE* temporal lobe epilepsy, *FTD* fronto-temporal dementia, *mPFC* medial prefrontal cortex, *MCI* mild cognitive impairment, *CHI* closed head injury

12.2.1 JOLs are Dissociable from Memory

A central question in metamemory research has been whether or not metamemory exists as something outside of memory. Neuropsychological studies have demonstrated dissociations between memory and JOLs, demonstrating that the two processes are at least partially independent [29, 90, 91] (Table 12.2). Converging evidence has also been found using event-related potentials (ERPs) [84] and functional magnetic resonance imaging (fMRI) [34, 45] (Table 12.1).

Patients with lesions to the frontal cortex tend to show impaired JOLs, either with intact memory [91], or impaired memory [90]. In one study, right frontal patients showed impaired global JOLs and intact memory for locations of faces, whereas patients with right posterior lesions showed intact global JOLs and impaired memory for locations of faces [91]. This double dissociation nicely demonstrates that memory and metamemory are separable, at least in the case of global JOLs (Cosentino, this volume). Similar work has been shown in word list learning paradigms with right frontal patients showing impairments in global JOLs compared to patients with posterior regions [90]. To further illustrate the double dissociation, patients with temporal lobe epilepsy (TLE) have impaired memory and intact JOLs [1, 29, 30]. Taken together, these findings suggest that the frontal cortex, and not the temporal lobes, is critical for JOLs.

Functional MRI and ERP studies also show that JOLs are separable from memory processes. Do Lam et al. [45] scanned participants during encoding and immediate JOLs, as separate tasks. There was a greater activity in the medial prefrontal cortex (mPFC) and orbitofrontal cortex (OFC) when participants made JOLs, even when encoding-related activity was masked out. Other regions showed similar levels of activity during JOLs and encoding. Interestingly, ERPs, which have excellent temporal resolution, have been able to narrow the similarities between JOLs and ERPs to early time windows, and differences between JOLs and encoding to late time windows [84]. Taken together, there is considerable evidence that JOLs cannot be reduced to memory processes alone.

In summary, the majority of evidence from neuroimaging and neuropsychology suggests that JOLs are separable from metamemory, and that the frontal cortex is important in JOLs and memory, whereas the temporal lobes are mainly important in memory processes and are not critical for JOLs. The nature of the processes carried out by the frontal cortex, and the specific locations within the frontal cortex, are informed by further data examining brain regions that modulate based on (1) the subjective level of JOL expressed, (2) the accuracy of the JOLs, and (3) the cognitive bases for JOLs.

12.2.2 The Rating Scale: Higher Versus Lower JOL

Critical to understanding the cognitive neuroscience of JOLs is examining the subjective rating expressed. TLE patients were able to use the JOL rating scale similarly to controls [29, 30], suggesting that other brain regions are responsible for signaling the subjective rating. Neuroimaging data are particularly valuable for this kind of understanding because they allow data analyses on a trial-by-trial basis, with the ability to directly compare trials with higher and lower ratings (Table 12.1). Kao et al. [34] used fMRI and examined which regions showed greater activity for predicted memory formation (i.e., High JOL vs. Low JOL) compared to actual memory formation (i.e., Remembered vs. Forgotten), and showed that the dorsal mPFC, anterior cingulate cortex (ACC), and left lateral prefrontal cortex (PFC) showed differences in activity for JOLs beyond actual memory performance. Similarly, in an associative memory task that isolated the JOL trial, there was greater activity in mPFC, OFC, and ACC for high versus low JOLs [45]. It is worth noting that the ACC activation reported by Kao et al. [34] is much more anterior (MNI coordinates: 4, 42, −4) than that reported by Do Lam et al. [45] (MNI coordinates: −4, 8, 30). Although fMRI work points most consistently to mPFC being modulated by JOL, topographic analyses of ERP data show a more centro-posterior component distinguishing high and low JOLs [84]. However, given the spatial resolution of ERPs and its poor ability to detect medial sources, it is unclear how these data map onto the fMRI data. Nevertheless, the fMRI literature suggests that activity in the mPFC modulates by the subjective JOL expressed most consistently, and other regions may vary based on stimuli and/or task demands.

As shown above, the most consistent region that modulated based on the subjective level of the JOL rating was the mPFC. Other non-metamemory fMRI studies have consistently shown greater activity in this region when engaged in self-referential processing (e.g., [27, 31, 35]), and also when reasoning about the mental states of others (e.g., [54, 71]). JOLs require introspecting on one's own memory, and it is likely that the activity in the mPFC reflects monitoring one's own mental state. Knowing which regions distinguish higher and lower JOLs is useful, but a fuller understanding of the cognitive neuroscience of JOLs is gained by examining the interactions between memory and JOLs.

12.2.3 Accurate JOL

One of the goals in research on metamemory is to determine the antecedents of accurate JOLs (i.e., when memory prediction is congruent with memory accuracy). The most common metamemory accuracy metric used is the Goodman–Kruskal Gamma coefficient. The ventral mPFC (vmPFC) was significantly correlated with the Gamma coefficient during accurate JOLs, but not inaccurate JOLs [34]. Findings from patients with frontal lesions have shown similar findings, with patients showing less accurate global JOLs compared to controls and patients with posterior lesions [90, 91]. However, patients with dysexecutive syndrome, presumably a prefrontal disorder, showed similar JOL accuracy, as measured by the Gamma coefficient, to controls [63]. Although there is some mixed evidence for the role of the frontal cortex in accurate JOLs, most evidence from fMRI (Table 12.1) and lesion studies (Table 12.2) suggest that the vMPFC is the most likely candidate for making accurate JOLs, but given the paucity of studies, further research is needed.

The vmPFC showed sensitivity to the subjective level of JOL rating expressed and JOL accuracy [34]. In other domains, the vmPFC has been implicated in encoding a value signal which then gets used for goal-directed behavior (e.g., [24]). Logically, it seems plausible that the vmPFC in JOLs reflects weighing of mnemonic evidence, analogous to its value, and deciding whether the information was learned well enough to warrant a particular judgment.

12.2.4 Basis of JOL

Critical to our understanding of JOLs is knowing what forms the basis of the judgment. Because JOLs are made about how well information is encoded, the most obvious basis for a JOL is the encoding phase. Kao et al. [34] used a masking procedure to examine which brain regions were activated for both actual encoding success and predicted encoding success, and showed that the lateral PFC was involved in both encoding and JOLs. This suggests that the same processes that contribute to successful encoding also contribute to JOLs. One possibility is that increased lateral PFC activity signals increased effort at encoding, which influences both the memory outcome and the JOL. Another hypothesized explanation for the lateral PFC activity was that it reflected partial retrieval of the target in working memory. Logically, this would mean that JOLs could be based, in part, on retrieval mechanisms.

In order to test the idea that retrieval operations influence JOLs, Do Lam et al. [45], used an inclusive masking approach to examine regions that showed increased activation associated with both memory predictions and successful recall. The mPFC was associated with both recall and JOLs. More generally, the mPFC has been implicated in performance monitoring (e.g., [69]), suggesting that in JOLs the vmPFC may be monitoring memory performance with respect to the recalled candidate information. Correspondingly, ERPs have also shown similar components for JOLs and recognition using a face task [85]. Thus, although JOLs are made in reference to encoding, it appears that individuals engage in retrieval processes to test how well they have learned information.

In addition to factors related to encoding and retrieval processes, more inferential factors may also influence JOLs. One study directly addressing this issue examined the role of distinctiveness in facial recognition and JOLs [85]. Two groups of subjects participated in a facial recognition task, with one group giving JOLs and the other giving distinctiveness ratings while ERPs were recorded. Behaviorally, individuals in the JOL group reported using distinctiveness to make their judgments, and distinctiveness ratings were just as predictive of recognition performance as JOLs. There were similar ERPs for distinctiveness ratings and

JOLs, and, assuming that similar patterns of brain activity reflect similar cognitive processes, JOLs in this paradigm were likely to have been based on distinctiveness. The use of distinctiveness may depend on the specific task, so further work using other tasks and other relevant factors is needed. Nevertheless, initial evidence shows the brain imaging can be an useful tool for investigating the bases of JOLs, and that, in addition to encoding and retrieval operations, inferential factors also influence JOLs.

12.3 Feeling-of-Knowing

Closely related to delayed JOLs is the feeling-of-knowing (FOK), but FOK differs from the delayed JOL in that it pertains only to non-recallable information. Similar to JOLs, FOK is a prospective metamemory judgment, and is made about future memory performance. The typical FOK paradigm uses a recall-judgment-recognition (RJR) task design [25]. In an RJR task, participants are asked to recall some target information. If they are unable to recall the information, participants make judgments of how likely they are to remember it at a later time, which constitutes the FOK judgment. Following the FOK judgment, they are presented with a recognition test and asked to choose the correct answer among a set of alternatives.

12.3.1 FOK is Dissociable from Memory

FOK has been shown to be a reasonable indicator of memory by demonstrating that having a high FOK for a non-recallable item results in a greater probability of successful subsequent recognition [25]. Because FOK has been related to memory accuracy, a critical question is whether FOK is merely an intermediate retrieval state between recognition and recall, or whether FOK judgments are dissociable from memory. One way to examine whether FOK is distinct from memory is to examine metamemory and memory performance in neuropsychological populations (e.g., [6, 61, 62, 73]) (Table 12.2). Several neuropsychological studies have highlighted the importance of the prefrontal cortex in FOK [6, 75]. Schnyer et al. [75] showed that frontal patients were impaired on FOK judgments compared to controls. However, these patients also showed worse memory performance, making it harder to interpret those data because there needs to be some minimum level of mnemonic information to monitor for metamemory to be accurate [41, 55]. Indeed, Schnyer et al. [75] performed covariate analyses and showed that memory did contribute to metamemory, but was not the only factor. Despite issues with memory accuracy, patients with the greatest impairments in FOK had more medial lesions, and they did not show the lowest performance. Another study was able to more directly test the role of the mPFC in FOK by examining instances when memory was matched in patients and controls, and the mPFC patients still showed significantly worse FOK accuracy compared to controls [55]. Although there are some ambiguities in the literature when memory performance differs between patients and controls, the majority of evidence suggests that memory and metamemory processes are dissociable and the mPFC is critical for accurate FOK judgments.

A second approach to examining whether memory and metamemory are separable is to use fMRI to compare metamemory and memory tasks [17–19] (Table 12.1). Compared to recognition, making an FOK judgment showed greater activity in the vmPFC, bilateral superior frontal, mid and posterior cingulate, and large lateral parietal/temporal area, including the inferior parietal lobule, the tempo-parietal junction (TPJ), and the superior temporal gyrus [19]. Collectively, these regions have been thought of as the "default" network (e.g., [11, 64, 65]), which has been implicated in internally directed thought (e.g., [52, 64]), mental simulation (e.g., [12]), and the self (e.g., [23]), all of which are relevant to FOK judgments. The vmPFC finding is consistent with lesion work, but it remains an open question whether a lesion in any part of this network would disrupt FOK judgments. Regardless, consistent converging evidence from lesion and fMRI studies indicate that FOK and memory are separable.

12.3.2 Levels of FOK

Another important aspect to understanding how the brain gives rise to metamemory is knowing which brain regions modulate based on the subjective level of FOK expressed (Table 12.1). Recent evidence has shown graded activation for FOK judgments, with greater activity for higher than lower levels of FOK [36, 37, 49, 74]. Earlier studies showed FOK as an intermediate level of activity between successful recall and failed recall in multiple prefrontal regions [37], or between successful recall and "don't know" response in left PFC, left posterior parietal cortex (PPC), and the ACC [49]. Similarly, comparisons of High versus Low FOK ratings showed greater activity in the ventrolateral PFC (VLPFC) and dorsolateral PFC (DLPFC) [19] and ventral PPC [22]. Few studies have reported greater activity for Low FOK compared to High FOK in any regions, but Elman et al. [22] showed this in the dorsal PPC. Similar patterns of ascending activity for higher compared to lower FOK ratings have been shown using a finer scale that rated FOK on a scale of 1–6 [36]. Several regions showed significant linear relationships to the FOK ratings including: the VLPFC, DLPFC, anterior PFC (aPFC), mPFC, cingulate cortex, as well as temporal and parietal regions. Altogether, these findings show the most consistent modulation of brain activity by subjective level occurs in the frontal cortices, with growing evidence that the PPC also modulates by subjective level.

12.3.3 Tip-of-the-Tongue: More than FOK?

Related to different levels of FOK is the tip-of-the-tongue (TOT) phenomenon, which is a subjective state that involves unsuccessful recall but a strong feeling that retrieval is imminent [10, 51, 77]; Diaz and Schwartz, this volume). Some TOT research focuses on linguistic aspects [80, 81], but here we will focus on meta-memorial aspects. Kikyo et al. [38] made inferences about TOTs and suggested that TOTs elicited activation in the left DLPFC and the ACC. Maril et al. [51] used explicit behavioral responses to sort TOT trials and showed greater activation in the right middle frontal gyrus and ACC during TOT states compared to "Know" and "Don't Know" responses. Considering that the ACC has been implicated in conflict monitoring and effortful tasks (e.g., [9]), it is not surprising that it is active during TOT states, which are often described as frustrating and require effortful searching.

There is controversy over whether TOT and FOK are the same process, with TOT being a strong FOK (e.g., [3]), or whether the processes for FOK and TOT are distinct [50, 76]. One way to gain leverage on this controversy is to compare the neural correlates of TOT and FOK [38, 50]. When directly comparing FOK and TOT states, Maril et al. [50] found that TOT elicited greater activation in the ACC, right DLPC, right inferior PFC, and bilateral aPFC. However, both TOT and FOK elicited similar activation in the posterior medial parietal cortex and bilateral superior PFC. Taken together these findings suggest that, although there is some overlap with FOK, there are distinct brain regions responsible for the TOT state, most likely related to the feelings of frustration, conflict, imminent retrieval, or the decision to continue attempted retrieval.

12.3.4 Accurate FOK Judgments

In addition to studying the levels of FOK, researchers have also investigated accurate versus inaccurate FOK judgments. An accurate FOK judgment is consistent with performance at recognition, whereas an inaccurate FOK judgment is inconsistent with performance at recognition. Converging evidence from lesion [75] (Table 12.2) and fMRI studies [74] (Table 12.1) have implicated the mPFC in accurate FOK judgments. Specifically, frontal patients showed lower FOK accuracy, as measured by the Gamma correlation, a measure of relative accuracy, and Hamann index, a measure of absolute accuracy, compared to controls [75]. In a subsequent fMRI study, Schnyer et al. [74] compared accurate to inaccurate FOK judgments, and showed activation in a left hemisphere network of frontal and temporal cortical regions, including the medial and lateral frontal cortex, the hippocampus and parahippocampal gyrus, and the middle temporal gyrus. However, some areas in the right frontal cortex were also active, specifically the inferior frontal gyrus and the ACC.

Although Schnyer et al. [74] showed significant differences in activation for accurate and inaccurate FOK, several other studies that have tried to examine the full range of accurate and inaccurate FOK responses have not shown any significant differences [19, 32]. Indeed, when comparing High FOKs followed by correct recognition (an accurate FOK) to Low FOKs followed by incorrect recognition (an accurate feeling-of-not-knowing), there was greater activity in the left middle frontal gyrus [32]. This could explain why many studies that group different types of accurate FOKs (High FOKs followed by correct recognition and Low FOKs followed by inaccurate recognition) together and group different types of inaccurate FOKs together (High FOKs followed by incorrect recognition and Low FOK followed by correct recognition) often fail to find differences for accurate and inaccurate FOK.

12.3.5 Basis of FOK

A critical question that then arises is: on what are people basing these feelings-of-knowing or feelings-of-not-knowing? The leading hypotheses about how people make FOK judgments are: (1) cue familiarity (e.g., [53, 67, 78], (2) partial access to the sought-after information (e.g., [41, 42], or (3) a combination of cue familiarity and accessibility (e.g., [43]). Cognitive neuroscience research has only recently started to address these questions, and current evidence suggests that the mPFC plays a role in assessing accessibility of the retrieved information [74, 75]. Patients with mPFC damage who show impaired FOK, are able to make familiarity-based judgments, thus eliminating cue familiarity as a basis for their deficit in FOK [75]. More direct evidence comes from an fMRI study that used structural equation modeling to show that vMPFC activity was related to monitoring the outputs of retrieval, or content accessibility [74].

Different types of tasks, such as episodic versus semantic memory, appear to lead to FOK judgments based on different factors. Some participants show deficits in episodic FOK, but not semantic FOK [86]. Furthermore, evidence from fMRI shows that although some brain areas modulate based on level of FOK regardless of whether the information is episodic or semantic, other regions are task-specific [22, 68]. As one might expect, semantic FOKs activated the anterior temporal cortex, which has been associated with semantic knowledge, whereas strong episodic FOKs activated the ventral PPC, which is known to be involved in episodic retrieval [22], suggesting that the basis of FOK is task-sensitive. Broadly, this highlights the need to consider the bases of the FOK judgment across different studies.

12.4 Retrospective Confidence Judgments

Retrospective confidence judgments (RCJs) differ from prospective JOLs and FOKs, in that they require assessing one's confidence after recall or recognition. In neuroimaging, recognition tasks are more commonly used because of challenges in collecting verbal responses, so we will mainly focus on RCJs associated with recognition. Experimental tasks measure confidence by asking the participant to judge how confident they are in their recognition judgments, and either simultaneously with the recognition judgment (e.g., "sure old", [39, 40, 56]), or in a two-step process by asking the participant to rate their confidence immediately following a retrieval task [17–19]. Confidence judgments have been used outside of metamemory research, and have often been used in memory studies to assess the strength of the memory trace (e.g., [88]), or to separate recollection and familiarity (e.g., [66, 95, 97]). Although those studies are informative, their focus tends to make them difficult to interpret in terms of metamemory. Therefore, we have confined our review to studies that have a specific focus on confidence in recognition memory.

12.4.1 RCJs are Separable from Memory

Behavioral research shows that confidence and accuracy may be based on partially overlapping information (for review, see Busey et al. [14]), and are often positively correlated [46, 88, 95], raising the question of whether confidence and accuracy are separable. However, in several circumstances people report high confidence in memories that have never happened [47, 59, 70, 72]. Therefore, memory confidence and memory accuracy must rely, at least partly, on different information, and have different neural substrates.

The most direct evidence that recognition and confidence judgments are different processes comes from fMRI studies comparing these two tasks (Table 12.1). Compared to recognition, there was greater activity in bilateral PPC, insula, bilateral PFC, posterior cingulate cortex (PCC), and the right OFC during confidence judgments [17, 19]. These are similar to the "default network" [64] regions that were also involved in making FOK judgments.

Given that the fMRI studies highlight the parietal cortex in RCJs, a critical question is whether patients with lesions to the parietal cortex exhibit a dissociation between memory and metamemory. There is some anecdotal [21] and experimental [83] evidence that patients with parietal lesions may have impairments in retrospective confidence despite little or no impairment in memory tasks [8, 21, 82]. Experimentally, one parietal lesion patient, SM, showed lower conscious recollection rates compared to controls, using the "remember/know" paradigm [21]. From this finding, it is unclear whether this is a deficit in recollection or in the subjective experience associated with remembering. Anecdotal evidence from this patient suggests it is related to her subjective experience because (1) SM complained that she did not feel like she knew where her memories came from, (2) SM could not assess her confidence for the memories she retrieved, and (3) SM second-guessed many accurate recognition judgments, often asking for feedback on whether she was right or wrong.

In a study designed to tease apart recollection and subjective confidence, Simons et al. [83] showed a dissociation in memory accuracy and memory confidence in patients with parietal lesions. Across three experiments, patients and controls completed (1) old/new item recognition tasks with confidence judgments, and (2) source recollection tasks with confidence judgments. Patients with parietal lesions had significantly decreased confidence ratings compared to controls in the source recollection task, yet patients and controls had similar accuracy in their source judgments. Consistent with the idea that the parietal cortex is critical in subjective aspects of memory, such as confidence, TMS to the inferior parietal cortex showed a greater effect on subjective than objective memory performance [79]. Further brain stimulation studies that investigate the role of the frontal and parietal cortices in subjective confidence provide a promising avenue to investigate some of these issues further.

12.4.2 Regions that Modulate Based on the Subjective Confidence Level Expressed

In addition to understanding which brain regions are involved in the process of confidence assessment, it is also critical to know which brain regions modulate based on the subjective *level* of confidence expressed (Table 12.1). This includes understanding which regions show greater activity for high compared to low confidence responses, and which ones show greater activity for low compared to high confidence responses.

Similar to other metamemory judgments, regions in the PFC have been shown to modulate by the level of confidence expressed. However, unlike the other judgments, there is typically more prefrontal activity with lower levels of confidence [18, 26, 28]. Early work, using a single step design, implicated the lateral PFC with increased monitoring because there was greater activity in the right DLPFC for low confidence correct compared to high confidence correct item recognition judgments, regardless of whether the item was judged old or new [28]. Consistent with this, source memory paradigms have also shown greater activation in the VLPFC for low compared to high confidence recognition [26], and there were also greater evoked potentials (FN400) during low confidence than high confidence RCJs over the lateral PFC [93]. The previous studies were limited in that they examined only correct responses and used simultaneous confidence and recognition tasks, but Chua et al. [18] showed greater activity in the DLPFC, VLPFC, and ACC for low compared to high confidence responses for both correct and incorrect recognition in a two step judgment. Thus, these studies largely relate the PFC to low confidence recognition, a condition which is thought to require greater monitoring.

The PPC also plays an important role in signaling the subjective level of confidence expressed, and fMRI studies have indicated that superior and inferior parietal regions may play different roles in the way they signal subjective memory confidence (e.g., [18, 39]). Greater activity for high compared to low confidence in the *inferior* parietal cortex has been shown when individuals make separate confidence judgments [17], for true and false recognition [39], for hits and correct rejections [40], and for item and source memory [26]. In contrast, many of these studies have also shown greater activity in the *superior* parietal cortex for low compared to high confidence. Similarly, this holds true for studies of true recognition [39], item and source memory [26], for hits, misses, false alarms, and correct rejections [56], and hits and correct rejections [40]. Although there have been many consistencies, it is worth noting that the opposite patterns have been shown [18]. One interpretation of the typical inferior/superior distinction is that the parietal cortex is sensitive to the strength of memories. Differences that stray from these findings may reflect cases when individuals are using factors other than memory strength to make their confidence judgments. Future studies that manipulate the basis of the confidence judgment could shed light on some of these issues.

12.4.3 Basis of Recognition Confidence Judgments

Few neuroimaging studies have directly investigated confidence judgments based on different sources of information (e.g., memory strength vs. inferential processing; episodic vs. semantic; true vs. false recognition). Although there are many similarities in the regions that modulate by subjective confidence, the differences may reflect different bases for the confidence judgments. Kim and Cabeza [39] compared high and low confidence in memory for situations that were presumably based on different information: true and false recognition. False recognition in this paradigm relied on gist representations, thus allowing examination of high confidence false recognition when specific details of the remembered item are not present, which can then be compared to true recognition. For true recognition, frontal and parietal regions were significantly more activated for low confidence than high confidence responses, while medial temporal regions were significantly more activated for high confidence than low confidence responses. Conversely, for false recognition, medial temporal regions were significantly more activated for low confidence than high confidence, whereas frontal and parietal regions were significantly more activated during high confidence than low confidence [39]. Thus, patterns of activation associated with high and low confidence are related to the basis for those judgments.

12.4.4 Accuracy of the Confidence judgments

An outstanding issue is whether there are brain regions that contribute to accurate RCJs (i.e., confidence judgments that are congruent with memory accuracy). Because individuals vary in how well their confidence predicts their accuracy, we can correlate brain activity with the ability to make accurate confidence judgments (Table 12.1). Yokoyama et al. [94] first compared which regions activated more for RCJs compared to a control task (i.e., brightness discrimination). Second, they examined which voxels within these regions correlated with metamemory accuracy, as measured by the Gamma coefficient. The only region whose activity correlated with accurate metamemory performance was the right frontopolar cortex, suggesting this specific region is important in accurate self-monitoring. Although the frontopolar activity correlates across individuals, one necessary analysis is to compare accurate and inaccurate RCJs at the trial level within individuals. Thus far, many of these analyses have shown no significant differences in accurate and inaccurate trials [17–19]. Thus, it may be that variation in frontal function is related to the ability to make accurate RCJs, rather than frontopolar cortex being a signal for an accurate judgment.

To summarize, converging evidence from lesion, neuroimaging and electrophysiology consistently implicate the PFC and PPC during RCJs. These regions have various roles in making a confidence judgment, signaling the subjective level of confidence expressed, and leading to accurate confidence judgments. The prospective memory tasks discussed earlier mainly centered on prefrontal regions, and RCJs implicated the parietal cortex as also having an important role in metamemory. Explicitly comparing the neural substrates of the different tasks may help us elucidate the common neural mechanisms supporting the general demands involved in metamemory, and distinct mechanisms related to specific metamemory tasks.

12.5 Common and Distinct Metamemory Mechanisms

Thus far, we have examined three aspects of the brain mechanisms subserving three major metamemory tasks [19] by reviewing brain regions that: (1) are involved in metamemory *processes*, (2) modulate based on the subjective *level* of the judgment, and (3) correlate with *metamemory accuracy*. Next, we compare tasks across these three aspects (Tables 12.1 and 12.2).

12.5.1 Metamemory Processes

One hypothesis is that the process of metamemory monitoring, during which an individual turns his or her focus inward to the contents of memory, is consistent and reflects a universal component of metamemory. In contrast, it could be that the metamemory monitoring mechanisms differ depending on the task and the type of information being monitored.

There is good evidence that metamemory tasks share common processes (Table 12.1), most directly from comparisons of FOK and RCJ to non-metamemory tasks [19]. Both FOK and RCJ showed greater activity in the left and right TPJ, left and right superior temporal gyrus, vmPFC, and PPC, compared to recognition and attractiveness judgments. There was also consistently less activity in occipital, lateral PFC, and dmPFC during metamemory tasks compared to non-metamemory tasks. This indicates that there are common mechanisms supporting FOK and RCJ. It is more difficult to compare JOLs to these findings because JOLs are often compared to encoding, rather than retrieval. However, JOLs have been shown to activate the mPFC [45]. This provides indirect evidence that JOLs may also engage some of the same brain regions as other metamemory tasks, but further work is clearly needed.

The pattern of relative activations and deactivations seen when comparing metamemory monitoring and memory tasks suggests that the common processes of metamemory consist of shifting toward internal thoughts and away from external stimuli [19]; (see also Fox and Christoff, this volume). The vmPFC, lateral PPC, and PCC regions that showed greater activity for metamemory compared to non-metamemory tasks have previously been characterized as being part of the "default network" [11, 13, 23, 64]. Further characterization of the functions of the default network has implicated self-related processing, directing attention to internal processing, and mental simulation [12, 23, 64]. Metamemory is thought to engage all of these in the sense that it involves self-reflection, directing attention to internal thoughts and memory representations, and simulating the contents of memory. Furthermore, the regions that showed relative deactivations for metamemory compared to non-metamemory—less activation in the occipital cortex and the lateral prefrontal cortex—are consistent with less attention to the external environment [20].

In addition to shared mechanisms between metamemory tasks, fMRI has shown differential activation when directly comparing FOK and RCJ [19]. These likely reflect that FOK and RCJ are based on different sources of information. For example, there was greater activity in the left aPFC for RCJ than FOK, and greater activity in the hippocampus for FOK compared to RCJ [19], likely reflecting increased memory demands during the FOK task, which has been shown to rely, at least in part, on partial access to the to-be-retrieved information (e.g., [41]). Additionally, there was greater activity in the fusiform gyrus, which has been shown to be active during face processing (e.g., [33]), for FOK compared to RCJ. This likely reflects that in this paradigm, the cue was a face, and FOK may rely on cue familiarity (e.g., [53]).

12.5.2 Subjective Levels of the Metamemory Judgment

The next question is whether there are brain regions that modulate based on the subjective level of the metamemory judgment, regardless of the task. One possibility is that there are regions that signal overall certainty or doubt in one's memory, or may reflect that different amounts of monitoring occur under such conditions of certainty or doubt. However, it is also likely that the subjective judgment expressed is related to the specific bases of the different metamemory judgments, and would, therefore, differ across tasks (Table 12.1).

Direct comparisons have shown that different brain regions modulate based on the level of FOK or RCJ expressed. Chua et al. [19] showed greater activity in aVLPFC and aDLPFC for high compared to low FOK judgments. However, there were no differences based on the level of RCJ in these regions. These differences likely relate the fact that FOK and RCJ are based on different information.

However, comparisons across studies have suggested that some metamemory tasks may signal subjective level similarly. The lateral PPC may modulate based on both the level of FOK (e.g., [36, 49]) and RCJ (e.g., [26, 40, 56]). These effects may be more apparent in single task metamemory studies, and not in Chua et al. [19] because of increased power due to increased trial number. Both FOK and RCJs are given at retrieval and are thought to be based on either partial or full access to the sought after information. There are currently many theories being investigated about the role of the PPC in retrieval, some of which are very relevant to metamemory, including attention to memory, accumulation of mnemonic evidence, and decision making in relation to retrieval (for review, see [92]). Similarly, comparisons across studies suggest the subjective level expressed for FOK and JOLs may share common neural correlates in the PFC [19, 34, 36, 45, 49]. For JOL and FOKs, cue familiarity has been suggested as a shared monitoring process in JOLs (e.g., [44]) and FOK judgments (e.g., [78]), and the increasing PFC activity may relate to increasing familiarity (e.g., [96]).

On the whole, extant evidence suggests that there are no brain areas that signal certainty or doubt across different metamemory tasks. Instead, there are some commonalities across prospective tasks and across retrieval-based tasks, suggesting that brain regions that signal the subjective level of the judgment are specific to the basis of the judgment.

12.5.3 Metamemory Accuracy Across Types of Judgments

Anterior frontal regions have been implicated in metamemory accuracy, but these tend to be medial for JOLs [34] and FOK [55, 74, 75], and more lateral for RCJs [94] (Table 12.1). Consistent with the medial-lateral distinction, Schnyer et al. [75] showed that patients with more medial lesions were impaired on FOK, but intact on RCJ. In contrast, patients with more lateral lesions were impaired at RCJ, but not FOK [61]. In a study looking at patients with more circumscribed lesions on multiple metamemory tasks, Modirrousta and Fellows [55] showed that when patients with mPFC lesions were equated for memory performance with controls, patients were impaired on FOK, but not on RCJ or global JOLs. Given that the neuroimaging literature has suggested that trial-by-trial JOLs activate the mPFC, further work in patients with mPFC lesions on trial-by-trial JOLs is necessary for determining whether the mPFC is critical for JOLs, and prospective metamemory in general. Nevertheless, current evidence suggests that the mPFC plays a critical role in accurate trial-by-trial FOK judgments, and not RCJ, whereas its role in trial-by-trial JOLs remains unclear.

Broadly speaking, the aPFC seems to be a prime candidate for accurate metamemory. Current evidence suggests that the aPFC sits at the top of a hierarchy, coordinating signals from the DLPFC and VLPFC, making the aPFC ideal for monitoring and manipulating internally generated information [2, 13, 15], which is a key aspect of metamemory monitoring. The distinctions between lateral PFC for RCJ accuracy, and mPFC for JOL and FOK accuracy, most likely stems from the predictive nature of JOLs and FOKs. Indeed, recent research has suggested that the mPFC is important in generating predictions [4, 5]. Further research is clearly needed given the relatively few studies on the cognitive neuroscience of metamemory. However, the existing evidence suggests that more medial regions of the anterior prefrontal cortex may play a role in accurate predictions, whereas more lateral regions of the anterior prefrontal cortex play a role in accurate postdictions (see also, Fleming and Dolan, this volume).

12.6 Conclusions

The Nelson and Narens [58] model has been extremely useful in providing a structure for excellent experimental work in cognitive psychology. Now, we are beginning to be able to understand how metamemory is represented in the brain. In this chapter, we laid out what we believe to be the critical pieces in understanding how the brain gives rise to metamemory. First, we must understand what brain regions are used during the act of engaging in the *process* of metamemory monitoring. Second, we need to understand which brain regions modulate based on the subjective *level* of the metamemory judgment. Third, we need to understand whether there are brain regions that signal an *accurate* metamemory judgment. Bringing these three together, we then need to know how the brain regions involved in process, level, and accuracy change when judgments are based on different sources of information. Comparing different metamemory judgments gives us some leverage on this, but we also need to explain why there may be different bases for the final judgment within a particular judgment class. We encourage researchers to expand on our current understanding of metamemory monitoring processes in the brain at these different levels, as well as aspects of metamemory related to strategies and other control processes.

References

1. Andrés P, Mazzoni G, Howard CE (2010) Preserved monitoring and control processes in temporal lobe epilepsy. Neuropsychology 24:775–786. doi:10.1037/a0020281
2. Badre D (2008) Cognitive control, hierarchy, and the rostro-caudal organization of the frontal lobes. Trends Cogn Sci 12:193–200. doi:10.1016/j.tics.2008.02.004
3. Bahrick HP (2008) Thomas O. Nelson: his life and comments on implications of his functional view of metacognitive memory monitoring. In: Dunlosky J, Bjork RA (eds) Handbook of memory and metamemory. Psychology Press, New York, pp 1–10

4. Bar M (2007) The proactive brain: using analogies and associations to generate predictions. Trends Cogn Sci 11:280–289. doi:10.1016/j.tics.2007.05.005
5. Bar M (2009) The proactive brain: memory for predictions. Philos Trans R Soc Lond B Biol Sci 364:1235–1243. doi:10.1098/rstb 2008.0310
6. Bastin C, Feyers D, Souchay C et al (2012) Frontal and posterior cingulate metabolic impairment in the behavioral variant of frontotemporal dementia with impaired autonoetic consciousness. Hum Brain Mapp 33:1268–1278. doi:10.1002/hbm.21282
7. Benjamin AS, Diaz M (2008) Measurement of relative metamnemoic accuracy. In: Dunlosky J, Bjork RA (eds) Handbook of memory and metamemory. Psychology Press, New York, pp 73–94
8. Berryhill ME (2012) Insights from neuropsychology: pinpointing the role of the posterior parietal cortex in episodic and working memory. Front Integr Neurosci 6:31. doi:10.3389/fnint.2012.00031
9. Botvinick MM, Cohen JD, Carter CS (2004) Conflict monitoring and anterior cingulate cortex: an update. Trends Cogn Sci 8:539–546. doi:10.1016/j.tics.2004.10.003
10. Brown R, Mcneill D (1966) The "tip of the tongue" phenomenon. J Verbal Learn Verbal Behav 7:325–337
11. Buckner RL, Andrews-Hanna JR, Schacter DL (2008) The brain's default network: anatomy, function, and relevance to disease. Ann N Y Acad Sci 1124:1–38. doi:10.1196/annals.1440.011
12. Buckner RL, Carroll DC (2007) Self-projection and the brain. Trends Cogn Sci 11:49–57. doi:10.1016/j.tics.2006.11.004
13. Burgess P, Dumontheil I, Gilbert S (2007) The gateway hypothesis of rostral prefrontal cortex (area 10) function. Trends Cogn Sci 11:217–248
14. Busey TA, Tunnicliff J, Loftus GR, Loftus EF (2000) Accounts of the confidence-accuracy relation in recognition memory. Psychon Bull Rev 7:26–48
15. Christoff K, Gabrieli JDE (2000) The frontopolar cortex and human cognition: evidence for a rostrocaudal hierarchical organization within the human prefrontal cortex. Psychobiol Austin 28:168–186
16. Chua EF, Rand-Giovannetti E, Schacter DL et al (2004) Dissociating confidence and accuracy: functional magnetic resonance imaging shows origins of the subjective memory experience. J Cogn Neurosci 16:1131–1142. doi:10.1162/0898929041920568
17. Chua EF, Schacter DL, Rand-Giovannetti E, Sperling RA (2006) Understanding metamemory: neural correlates of the cognitive process and subjective level of confidence in recognition memory. NeuroImage 29:1150–1160. doi:10.1016/j.neuroimage.2005.09.058
18. Chua EF, Schacter DL, Sperling RA (2009) Neural basis for recognition confidence in younger and older adults. Psychol Aging 24:139–153. doi:10.1037/a0014029
19. Chua EF, Schacter DL, Sperling RA (2009) Neural correlates of metamemory: a comparison of feeling-of-knowing and retrospective confidence judgments. J Cogn Neurosci 21:1751–1765. doi:10.1162/jocn.2009.21123
20. Corbetta M, Shulman GL (2002) Control of goal-directed and stimulus-driven attention in the brain. Nat Rev Neurosci 3:201–215. doi:10.1038/nrn755
21. Davidson PSR, Anaki D, Ciaramelli E et al (2008) Does lateral parietal cortex support episodic memory? Evidence from focal lesion patients. Neuropsychologia 46:1743–1755. doi:10.1016/j.neuropsychologia.2008.01.011
22. Elman JA, Klostermann EC, Marian DE et al (2012) Neural correlates of metacognitive monitoring during episodic and semantic retrieval. Cogn Affect Behav Neurosci 12:599–609. doi:10.3758/s13415-012-0096-8
23. Gusnard DA, Akbudak E, Shulman GL, Raichle ME (2001) Medial prefrontal cortex and self-referential mental activity: relation to a default mode of brain function. Proc Natl Acad Sci USA 98:4259–4264. doi:10.1073/pnas.071043098
24. Hare TA, Camerer CF, Rangel A (2009) Self-control in decision-making involves modulation of the vmPFC valuation system. Science 324:646–648. doi:10.1126/science.1168450
25. Hart JT (1965) Memory and the feeling-of-knowing. J Edu Psychol 56:208–216

26. Hayes SM, Buchler N, Stokes J et al (2011) Neural correlates of confidence during item recognition and source memory retrieval: evidence for both dual-process and strength memory theories. J Cogn Neurosci 23:3959–3971. doi:10.1162/jocn_a_00086
27. Heatherton TF, Wyland CL, Macrae CN et al (2006) Medial prefrontal activity differentiates self from close others. Social Cogn Affect Neurosci 1:18–25. doi:10.1093/scan/nsl001
28. Henson RN, Rugg MD, Shallice T, Dolan RJ (2000) Confidence in recognition memory for words: dissociating right prefrontal roles in episodic retrieval. J Cogn Neurosci 12:913–923
29. Howard CE, Andrés P, Broks P et al (2010) Memory, metamemory and their dissociation in temporal lobe epilepsy. Neuropsychologia 48:921–932. doi:10.1016/j.neuropsychologia.2009.11.011
30. Howard CE, Andrés P, Mazzoni G (2013) Metamemory in temporal lobe epilepsy: a study of sensitivity to repetition at encoding. J Int Neuropsychol Soc (JINS) 19:1–10. doi:10.1017/S1355617712001646
31. Jenkins AC, Mitchell JP (2011) Medial prefrontal cortex subserves diverse forms of self-reflection. Soc Neurosci 6:211–218. doi:10.1080/17470919.2010.507948
32. Jing L, Niki K, Xiaoping Y, Yue L (2004) Knowing that you know and knowing that you don't know: a fMRI Study on feeling of knowing (FOK). Acta Psychol 36:426–433
33. Kanwisher N, McDermott J, Chun MM (1997) The fusiform face area: a module in human extrastriate cortex specialized for face perception. J Neurosci 17:4302–4311
34. Kao Y-C, Davis ES, Gabrieli JDE (2005) Neural correlates of actual and predicted memory formation. Nat Neurosci 8:1776–1783. doi:10.1038/nn1595
35. Kelley WM, Macrae CN, Wyland CL et al (2002) Finding the self? An event-related fMRI study. J Cogn Neurosci 14:785–794. doi:10.1162/08989290260138672
36. Kikyo H, Miyashita Y (2004) Temporal lobe activations of "feeling-of-knowing" induced by face-name associations. NeuroImage 23:1348–1357. doi:10.1016/j.neuroimage.2004.08.013
37. Kikyo H, Ohki K, Miyashita Y (2002) Neural correlates for feeling-of-knowing: an fMRI parametric analysis. Neuron 36:177–186
38. Kikyo H, Ohki K, Sekihara K (2001) Temporal characterization of memory retrieval processes: an fMRI study of the 'tip of the tongue' phenomenon. Eur J Neurosci 14:887–892
39. Kim H, Cabeza R (2007) Trusting our memories: dissociating the neural correlates of confidence in veridical versus illusory memories. J Neurosci 27:12190–12197. doi:10.1523/JNEUROSCI.3408-07.2007
40. Kim H, Cabeza R (2009) Common and specific brain regions in high-versus low-confidence recognition memory. Brain Res 1282:103–113. doi:10.1016/j.brainres.2009.05.080.Common
41. Koriat A (1993) How do we know that we know? The accessibility model of the feeling of knowing. Psychol Rev 100:609–639
42. Koriat A (1995) Dissociating knowing and the feeling of knowing: further evidence for the accessibility model. J Exp Psychol Gen 124:311–333
43. Koriat A, Levy-Sadot R (2001) The combined contributions of the cue-familiarity and accessibility heuristics to feelings of knowing. J Exp Psychol Learn Mem Cogn 27:34–53. doi:10.1037//0278-7393.27.1.34
44. Koriat A, Ma'ayan H (2005) The effects of encoding fluency and retrieval fluency on judgments of learning. J Mem Lang 52:478–492. doi:10.1016/j.jml.2005.01.001
45. Do Lam ATA, Axmacher N, Fell J et al (2012) Monitoring the mind: the neurocognitive correlates of metamemory. PloS One 7:e30009. doi:10.1371/journal.pone.0030009
46. Lindsay DS, Read JD, Sharma K (1998) Accuracy and confidence in person identification: the relationship is strong when witnessing conditions vary widely. Psychol Sci 9:215–218. doi:10.1111/1467-9280.00041
47. Loftus EF, Pickrell JE (1995) The formation of false memories. Psychiatr Ann 25:720–725
48. Maki RH, Willmon C, Pietan A (2009) Basis of metamemory judgments for text with multiple-choice, essay and recall tests. Appl Cogn Psychol 23:204–222. doi:10.1002/acp.1440
49. Maril A, Simons JS, Mitchell JP et al (2003) Feeling-of-knowing in episodic memory: an event-related fMRI study. NeuroImage. doi:10.1016/S1063-8119(03)00014-4

50. Maril A, Simons JS, Weaver JJ, Schacter DL (2005) Graded recall success: an event-related fMRI comparison of tip of the tongue and feeling of knowing. NeuroImage 24:1130–1138. doi:10.1016/j.neuroimage.2004.10.024
51. Maril A, Wagner AD, Schacter DL (2001) On the tip of the tongue: an event-related fMRI study of semantic retrieval failure and cognitive conflict. Neuron 31:653–660
52. Mason MF, Norton MI, Van Horn JD et al (2007) Wandering minds: the default network and stimulus-independent thought. Science 315:393–395. doi:10.1126/science.1131295
53. Metcalfe J, Schwartz BL, Joaquim SG (1993) The cue-familiarity heuristic in metacognition. J Exp Psychol Learn Mem Cogn 19:851–861
54. Mitchell JP, Macrae CN, Banaji MR (2006) Dissociable medial prefrontal contributions to judgments of similar and dissimilar others. Neuron 50:655–663. doi:10.1016/j.neuron.2006.03.040
55. Modirrousta M, Fellows LK (2008) Medial prefrontal cortex plays a critical and selective role in “feeling of knowing” meta-memory judgments. Neuropsychologia 46:2958–2965. doi:10.1016/j.neuropsychologia.2008.06.011
56. Moritz S, Gläscher J, Sommer T et al (2006) Neural correlates of memory confidence. NeuroImage 33:1188–1193. doi:10.1016/j.neuroimage.2006.08.003
57. Nelson TO, Dunlosky J (1991) When people’s judgments of learning (JOLs) are extremely accurate at predicting subsequent recall: the “delayed-JOL effect”. Psychol Sci 2:267–270. doi:10.1111/j.1467-9280.1991.tb00147.x
58. Nelson TO, Narens L (1990) Metamemory: a theoretical framework and new findings. Psychol Learn Motiv 26:125–141
59. Norman KA, Schacter DL (1997) False recognition in younger and older adults: exploring the characteristics of illusory memories. Mem Cogn 25:838–848
60. Pannu JK, Kaszniak AW (2005) Metamemory experiments in neurological populations: a review. Neuropsychol Rev 15:105–130. doi:10.1007/s11065-005-7091-6
61. Pannu JK, Kaszniak AW, Rapcsak SZ (2005) Metamemory for faces following frontal lobe damage. J Int Neuropsychol Soc (JINS) 11:668–676. doi:10.1017/S1355617705050873
62. Perrotin A, Belleville S, Isingrini M (2007) Metamemory monitoring in mild cognitive impairment: evidence of a less accurate episodic feeling-of-knowing. Neuropsychologia 45:2811–2826. doi:10.1016/j.neuropsychologia.2007.05.003
63. Pinon K, Allain P, Kefi MZ et al (2005) Monitoring processes and metamemory experience in patients with dysexecutive syndrome. Brain Cogn 57:185–188. doi:10.1016/j.bandc.2004.08.042
64. Raichle ME, MacLeod aM, Snyder aZ et al (2001) A default mode of brain function. Proc Natl Acad Sci USA 98:676–682. doi:10.1073/pnas.98.2.676
65. Raichle ME, Snyder AZ (2007) A default mode of brain function: a brief history of an evolving idea. NeuroImage 37:1083–1090; discussion 1097–1099. doi:10.1016/j.neuroimage.2007.02.041
66. Ranganath C, Yonelinas AP, Cohen MX et al (2004) Dissociable correlates of recollection and familiarity within the medial temporal lobes. Neuropsychologia 42:2–13. doi:10.1016/j.neuropsychologia.2003.07.006
67. Reder L, Ritter F (1992) What determines initial feeling of knowing? Familiarity with question terms, not with the answer. J Exp Psychol 18:435
68. Reggev N, Zuckerman M, Maril A (2011) Are all judgments created equal? An fMRI study of semantic and episodic metamemory predictions. Neuropsychologia 49:1332–1342. doi:10.1016/j.neuropsychologia.2011.01.013
69. Ridderinkhof KR, van den Wildenberg WPM, Segalowitz SJ, Carter CS (2004) Neurocognitive mechanisms of cognitive control: the role of prefrontal cortex in action selection, response inhibition, performance monitoring, and reward-based learning. Brain Cogn 56:129–140. doi:10.1016/j.bandc.2004.09.016
70. Roediger H, McDermott K (1995) Creating false memories: remembering words not presented in lists. J Exp Psychol: Learn Mem Cogn 21:803–814

71. Saxe R, Moran JM, Scholz J, Gabrieli J (2006) Overlapping and non-overlapping brain regions for theory of mind and self reflection in individual subjects. Soc Cogn Affect Neurosci 1:229–234. doi:10.1093/scan/nsl034
72. Schacter DL, Dodson CS (2001) Misattribution, false recognition and the sins of memory. Philos Trans R Soc Lond B Biol Sci 356:1385–1393
73. Schmitter-Edgecombe M, Anderson JW (2008) Feeling-of-knowing in episodic memory following moderate-to-severe closed-head injury. Neuropsychologia 21:224–234
74. Schnyer DM, Nicholls L, Verfaellie M (2005) The role of VMPC in metamemorial judgments of content retrievability. J Cogn Neurosci 17:832–846
75. Schnyer DM, Verfaellie M, Alexander MP et al (2004) A role for right medial prefontal cortex in accurate feeling-of-knowing judgements: evidence from patients with lesions to frontal cortex. Neuropsychologia 42:957–966. doi:10.1016/j.neuropsychologia.2003.11.020
76. Schwartz BL (2008) Working memory load differentially affects tip-of-the-tongue states and feeling-of-knowing judgments. Mem Cogn 36:9–19. doi:10.3758/MC.36.1.9
77. Schwartz BL, Metcalfe J (2011) Tip-of-the-tongue (TOT) states: retrieval, behavior, and experience. Mem Cogn 39:737–749. doi:10.3758/s13421-010-0066-8
78. Schwartz BL, Metcalfe J (1992) Cue familiarity but not target retrievability enhances feeling-of-knowing judgments. J Exp Psychol Learn Mem Cogn 18:1074–1083
79. Sestieri C, Capotosto P, Tosoni A et al (2013) Interference with episodic memory retrieval following transcranial stimulation of the inferior but not the superior parietal lobule. Neuropsychologia 51:900–906
80. Shafto MA, Burke DM, Stamatakis EA et al (2008) On the tip-of-the-tongue: neural correlates of increased word-finding failures in normal aging. J Cogn Neurosci 19:2060–2070
81. Shafto MA, Stamatakis EA, Tam PP, Tyler LK (2009) Word retrieval failures in old age: the relationship between structure and function. J Cogn Neurosci 22:1530–1540. doi:10.1162/jocn.2009.21321
82. Simons JS, Mayes AR (2008) What is the parietal lobe contribution to human memory? Neuropsychologia 46:1739–1742. doi:10.1016/j.neuropsychologia.2008.05.001
83. Simons JS, Peers PV, Mazuz YS et al (2010) Dissociation between memory accuracy and memory confidence following bilateral parietal lesions. Cereb Cortex 20:479–485. doi:10.1093/cercor/bhp116
84. Skavhaug I-M, Wilding EL, Donaldson DI (2010) Judgments of learning do not reduce to memory encoding operations: event-related potential evidence for distinct metacognitive processes. Brain Res 1318:87–95. doi:10.1016/j.brainres.2009.11.047
85. Sommer W, Heinz A, Leuthold H (1995) Metamemory, distinctiveness, and event-related potentials in recognition memory for faces. Mem Cogn 23:1–11
86. Souchay C, Moulin CJA, Clarys D et al (2007) Diminished episodic memory awareness in older adults: evidence from feeling-of-knowing and recollection. Conscious Cogn 16:769–784. doi:10.1016/j.concog.2006.11.002
87. Spellman BA, Bloomfield A, Bjork RA (2008) Measuring memory and metamemory. In: Dunlosky J, Bjork RA (eds) Handbook of memory and metamemory. Psychology Press, New York, pp 95–116
88. Stretch V, Wixted JT (1998) Decision rules for recognition memory confidence judgments. J Exp Psychol Learn Mem Cogn 24:1397–1410
89. Thiede KW, Anderson MCM, Therriault D (2003) Accuracy of metacognitive monitoring affects learning of texts. J Educ Psychol 95:66–73. doi:10.1037/0022-0663.95.1.66
90. Vilkki J, Servo A, Surma-aho O (1998) Word list learning and prediction of recall after frontal lobe lesions. Neuropsychology 12:268–277
91. Vilkki J, Surma-aho O, Servo A (1999) Inaccurate prediction of retrieval in a face matrix learning task after right frontal lobe lesions. Neuropsychology 13:298–305
92. Wagner AD, Shannon BJ, Kahn I, Buckner RL (2005) Parietal lobe contributions to episodic memory retrieval. Trends Cogn Sci 9:445–453. doi:10.1016/j.tics.2005.07.001
93. Woroch B, Gonsalves BD (2010) Event-related potential correlates of item and source memory strength. Brain Res 1317:180–191. doi:10.1016/j.brainres.2009.12.074

94. Yokoyama O, Miura N, Watanabe J et al (2010) Right frontopolar cortex activity correlates with reliability of retrospective rating of confidence in short-term recognition memory performance. Neurosci Res 68:199–206. doi:10.1016/j.neures.2010.07.2041
95. Yonelinas AP (2001) Consciousness, control, and confidence: the 3 Cs of recognition memory. J Exp Psychol Gen 130:361–379
96. Yonelinas AP, Otten LJ, Shaw KN, Rugg MD (2005) Separating the brain regions involved in recollection and familiarity in recognition memory. J Neurosci 25:3002–3008. doi:10.1523/JNEUROSCI.5295-04.2005
97. Yonelinas AP, Parks CM (2007) Receiver operating characteristics (ROCs) in recognition memory: a review. Psychol Bull 133:800–832