3-8-2022

Signal Detection Analyses of the Relation of Prospective and Retrospective Metacognitive Judgments

Ali Pournaghdali
Apour005@fiu.edu

FLORIDA INTERNATIONAL UNIVERSITY

Miami, Florida

SIGNAL DETECTION ANALYSES OF THE RELATION OF PROSPECTIVE AND RETROSPECTIVE METACOGNITIVE JUDGMENTS

A dissertation submitted in partial fulfillment of

the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

COGNITIVE NEUROSCIENCE

by

Ali Pournaghdali

2022

To: Dean Michael R. Heithaus
College of Arts, Sciences, and Education

This dissertation, written by Ali Pournaghdali, and entitled Signal Detection Analyses of the Relation of Prospective and Retrospective Metacognitive Judgments, having been approved in respect to style and intellectual content, is referred to you for judgment.

We have read this dissertation and recommend that it be approved.

George Buzzell

Sang Wook Hong

Jorge Riera Diaz

Bennett L. Schwartz, Co-Major Professor

Fabian A. Soto, Co-Major Professor

Date of Defense: March 8, 2022

The dissertation of Ali Pournaghdali is approved.

Dean Michael R. Heithaus
College of Arts, Sciences, and Education

Andrés G. Gil
Vice President for Research and Economic Development
and Dean of the University Graduate School

Florida International University, 2022

DEDICATION

To my mom and dad. I cannot thank you enough for all your support, inspiration and encouragement. I hope you accept this dissertation as a small tribute.

To my wonderful brothers and sisters, for your unconditional love and support.

To my partner in crime; Chelsea, for your patient, understanding and support in this journey.

ACKNOWLEDGMENTS

My deepest gratitude to Dr. Bennett Schwartz for trusting and believing in me. I cannot use any words to describe how much I appreciate your impact on my life. My special gratitude to Dr. Fabian Soto for believing in my abilities and your exceptional mentorship during my doctoral studies.

Special thanks to my committee members Dr. Jorge Riera Diaz, Dr. Sang Wook Hong, Dr. George Buzzell and the late Dr. Bethany Reeb-Sutherland for your outstanding counsel and guidance. I would also like to thank Dr. Leslie Frazier and Dr. Shannon Pruden, former and current graduate program directors at the Department of Psychology, as well as Dr. Anthony Dick and Dr. Aaron Mattfeld, former and current Cognitive Neuroscience Program directors for all of their excellent support during my doctoral studies.

Finally, I would like to thank my wonderful research assistants, without whom completing a doctoral degree is impossible.

ABSTRACT OF THE DISSERTATION

SIGNAL DETECTION ANALYSES OF THE RELATION OF PROSPECTIVE AND RETROSPECTIVE METACOGNITIVE JUDGMENTS

by

Ali Pournaghdali

Florida International University, 2022

Miami, Florida

Professor Bennett L. Schwartz, Co-Major Professor

Professor Fabian A. Soto, Co-Major Professor

Tip-of-the-tongue states (TOT) and feeling-of-knowing judgments (FOK) are metacognitive experiences about the possibility of future retrieval of information when recall fails. Studies show that experiencing a TOT or a high FOK increases the possibility of correct retrieval of missing information, which demonstrates metacognitive sensitivity. However, evidence for metacognitive sensitivity of TOT and FOK mainly derives from measures that conflate metacognitive sensitivity with metacognitive bias. Moreover, no study has evaluated the influence of TOT and FOK judgments on the unbiased metacognitive sensitivity of other metacognitive experiences and judgments, in this case, confidence judgments.

In this study, I used general recognition theory (GRT) to provide a bias-free assessment of metacognitive sensitivity for TOT and FOK and to evaluate the influence of TOT and FOK on the metacognitive sensitivity of confidence judgments. In two experiments, I asked participants to perform a memory recall task. If recall failed, participants provided metacognitive judgments of TOT and FOK, memory recognition responses, and metacognitive judgements of confidence on those recognition responses. After collecting the behavioral data, I fit two different GRT models to the data to assess metacognitive sensitivity of TOT and FOK. Using estimated parameters of the models, I constructed two sensitivity vs. metacognition (SvM) curves, which represent sensitivity in the recognition task, as a function of strength of metacognitive experiences: an SvM curve for TOT and an SvM curve for FOK. In addition, to evaluate the influence of TOT and FOK on the metacognitive sensitivity of confidence judgments, I fit two different GRT models and constructed two additional SvM curves, which represents metacognitive sensitivity of confidence, as a function of strength of TOT and FOK judgments.

The results of the GRT-based analyses showed that experiencing TOT and a high FOK are associated with an increase in sensitivity in the memory recognition task and an increase in metacognitive sensitivity of confidence judgments. These results were the first bias-free indication of metacognitive sensitivity of TOT and FOK judgments and the first report of influence of TOT and FOK on metacognitive sensitivity of confidence judgments.

TABLE OF CONTENTS

LIST OF FIGURES

I. Introduction

What is Metacognition?

To understand the cognitive system and the nature of human and nonhuman minds, I argue that we should explore the subjective aspect of mind as well as objective behavior. That is, without an adequate understanding of subjective aspects of mind, our understanding of cognition will be deficient. By subjective aspects of mind, I mean the first-person experience that is unique to the person who is experiencing something (Tye, 1986). To use Thomas Nagel's words; "the fact that an organism has conscious [subjective] experience at all means, basically, that there is something it is like to be that organism" (Nagel, 1974, Page 436). The "something to be like of an organism" is the subjective aspect of mind and a puzzle that needs to be solved in order to better understand the nature of mind. There are several arguments as to what is the best way to study the subjective mind, or even if the subjective mind worth investigating (e.g., Chalmers, 1995, 2013; Dennett, 2018; Koriat, 2007; Lau, 2008; Lau & Rosenthal, 2011; LeDoux et al., 2020; Metcalfe & Schwartz, 2016; Michel et al., 2019). I argue that we can and should study subjectivity of the mind, and that, one way to do this is by studying metacognition (see also Knotts et al., 2018; Lau & Rosenthal, 2011; Rosenthal, 2019; Schwartz & Pournaghdali, 2016). In general, metacognition is the capacity of cognitive system to monitor and regulate itself (Koriat, 2007).

According to a classic model explaining metacognition (Nelson & Narens, 1990), the cognitive system is composed of two levels: an object-level that is responsible to construct a valid and truthful representation of the outside world and a meta-level that monitors the object-level and, if necessary, imposes control over object-levels processes (Nelson & Narens, 1990; see Fig. 1). That is, object-level processes and experiences are comprised of different cognitive processes and experiences that are in reference toward information that is being collected from the environment (such as perceptual and attentional processes) or already exist in the cognitive system (such as memory processes and mental imagery).

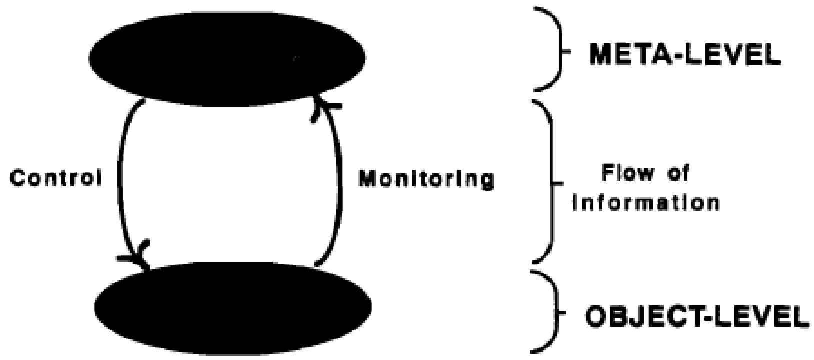

Fig. 1 Nelson and Narens's (1990) Model of Metacognitive Monitoring (from Nelson & Narens, 1990 by permission[1]). According to this model, the cognitive system is composed of a minimum of two levels: an object-level that is responsible to construct a valid and truthful representation of the outside world and a meta-level that monitors the object-level and, if necessary, imposes control over object-levels processes.

Meta-level processes are those that monitor the efficacy of such object-level processes and experiences, and if necessary, they can trigger control processes to adjust object-level processes according to a decision at the meta-level. For example, if a student does not feel confident about their ability to pass an exam, their metacognitive system directs them to study the material further. However, if this student feels that they know the material adequately, they may stop the learning process. Note that in this example, learning

[1] Permission license number: 5221371346185

is the object-level processes and student's confidence about their level of learning is the meta-level process. The final product of metacognitive monitoring in this example depends on the meta-level evaluation, which is either continuation or termination of learning.

The Variety of Metacognitive Judgments

Depending on the type and modality of object-level processes, the meta-level may create different experiences, leading to different judgments. Some of these judgments are in reference to the perceptual processes, and we call them perceptual metacognition (Mamassian, 2016). For instance, when being in a crossroad at night, one has to decide to keep going after a short stop or to stop longer and wait for other cars to pass. This decision depends first on the amount and validity of information in the perceptual system (both visual and auditory information), and then second on a metacognitive decision concerning the usefulness of that information. In this case, the metacognitive system has the responsibility of evaluating the validity of perceptual processes and decisions, and prompting the driver to act upon their decision. If the metacognitive system concludes that there is not enough information available in the perceptual system, it effectively warns the driver to be cautions. Otherwise, the metacognitive system will prompt the driver to proceed after a short stop.

Other metacognitive judgments are in references to the memory system, and we call them metamemory, metamnemonic, or metamemorial judgments (Nelson & Narens, 1990; Schwartz & Metcalfe, 2017). The metamemorial judgments evaluate the validity of memory system in different stages of information processing from memory encoding to memory retrieval (Metcalfe & Shimamura, 1994; Schwartz & Metcalfe, 2017). For example, while studying for an exam, a student may use metamemorial monitoring to judge if they are ready for the exam. If the metacognitive system reaches the conclusion that the student is ready for the exam, they stop studying further, otherwise the learning continues[2] (see Schwartz & Efklides, 2012).

In addition to classifying metacognitive judgments based on the cognitive/perceptual modality that they are evaluating; we can classify metacognitive judgments based on the temporal order of the judgments in relation to the object-level task (Fleming et al., 2016; Morgan et al., 2014). Based on this, we have two categories of metacognitive judgments: prospective metacognitive judgments that happen before a task performance and retrospective metacognitive judgments that happen after a task performance (also see Metcalfe & Schwartz, 2016). To clarify this categorization, one can think about a student who is studying for an important exam. If prior to taking the exam, we ask this student to rate their confidence about passing the exam, this student is using a prospective metacognitive judgment, because their metacognitive system is making a prediction about a task that is yet to happen. On the other hand, if we ask this student to rate their confidence concerning passing the exam, after taking the exam, this student is using a retrospective metacognitive judgment, because their metacognitive system is making an estimation regarding a task that has already happened before.

To summarize, we can categorize different metacognitive judgments as prospective or retrospective metacognitive judgments. Some of the most studied prospective metacognitive judgments are ease-of-learning (EOL; e.g., Jemstedt et al., 2017, 2018; Kornell et al., 2011), judgment-of-learning (JOL; e.g., Bjork et al., 2013; Nelson &

---

[2] Continuation or termination of study in this example is a metacognitive control.

Dunlosky, 1992; Rhodes & Tauber, 2011), feeling-of-knowing (FOK; e.g., Koriat, 2000; Metcalfe, 1986; Schwartz & Metcalfe, 1992) and tip-of-the-tongue (TOT; e.g., Schwartz & Cleary, 2016; Schwartz & Metcalfe, 2011; Schwartz & Pournaghdali, 2020) judgments. An example of retrospective metacognitive judgment that has been studies extensively is post-performance confidence ratings (henceforth confidence or confidence rating; e.g., Mamassian, 2016; Rahnev et al., 2020). In general, prospective and retrospective metacognitive judgments are the output of metacognitive monitoring of object-level processes, and they provide us with the outcome of monitoring processes (Nelson & Narens, 1990). For example, a confidence rating is the result of monitoring of the object-level processes and the decision based on those processes. That is, after monitoring the object level processes and decisions, metacognitive system may reach the conclusion that the decision is a valid and truthful one, and therefore, it will create a high level of confidence. Otherwise, metacognitive system creates a low level of confidence.

An interesting question is whether a general neurocognitive mechanism(s) generates all of the metacognitive judgments or if each metacognitive judgment has its own unique neurocognitive mechanism (e.g., McCurdy et al., 2013). This is a crucial question that has critical consequences for the scientific study of metacognition. For example, if all metacognitive judgments arise from a common neurocognitive mechanism(s), then we might ask how this mechanism(s) creates different metacognitive experiences. On the other hand, if each metacognitive judgment is based on a unique and specialized mechanism(s), then one can ask whether there is an interaction between different mechanisms supporting different metacognitive judgments. In line with this, one can ask if and then how different metacognitive judgments interact with each other[3]. For example, is it possible that having a tip-of-the-tongue experience influences the quality of our confidence when we remember the item in future?

An accurate evaluation of this question primarily depends on utilizing an accurate measure of metacognition, especially a measure of metacognitive sensitivity. As I will discuss in more detail later, research has shown that in most situations metacognitive judgments provide us with an accurate assessment of object-level processes. This is what we call metacognitive sensitivity (or resolution, see Fleming & Lau, 2014), and it refers to the precision of metacognitive judgment in predicting the accuracy of cognitive and perceptual processes. However, some of the methods used to estimate metacognitive sensitivity are not accurate, and factors other than metacognitive sensitivity may influence their estimations. Hence, to evaluate the influence of a metacognitive judgments on a different metacognitive judgment, we need a measure of metacognitive sensitivity that can provide us with an accurate estimate of metacognitive sensitivity and an accurate estimate of the interaction between different metacognitive judgments.

Based on these considerations, in this study I am interested in utilizing a multidimensional extension of signal detection theory called general recognition theory (Soto et al., 2015, 2017) to evaluate the metacognitive sensitivity of different metacognitive judgments and to evaluate the interaction between three metacognitive judgments: feeling-of-knowing and tip-of-the-tongue and confidence ratings. To this end, first I will provide

---

[3] It is important to note that such interaction is the result of interaction between the underlying processes of different metacognitive judgments and experiences.

an overall review of the literature on these three metacognitive judgments. Next, I will briefly review the studies that examined the possibility of general mechanism(s) that support different metacognitive judgments. Then, I will briefly review some of the common measures of metacognitive sensitivity, and then will discuss how we can evaluate metacognitive sensitivity of these three metacognitive judgments and the interaction between them using general recognition theory.

But first, it is important to briefly discuss terminology used in this branch of research. In this study, I will use terms *item*, *to-be-remembered item*, *target* and *to-be-remembered target* interchangeably to refer to something that a learner has to remember. For example, if a learner must remember the last name of the current US president, then that last name is a target or an item. On the other hand, I use term *cue* to refer to a question or information that is provided to a learner, in order for them to use it to remember an item. Note that the type of a cue depends on the type of memory that we are examining. For example, in a study that examines the memory for general-knowledge information, the general-knowledge question is the cue and in a study that examine the scene memory, the picture of a scene is the cue. In a study that asks participants to learn a word-pair and then present a word from each pair and asks participants to remember the other word, the presented word is a cue, and the word the participants must remember is the item or target. Having this terminology in mind, I will review and discuss tip-of-the tongue, feeling-of-knowing and confidence judgments next.

Tip-of-the-tongue

Tip-of-the-tongue states (TOT or TOTs) refers to the conscious metacognitive experience of imminent accessibility of an item when the memory system fails to recall that item (A. Brown, 1991; R. Brown & McNeill, 1966; Schwartz & Metcalfe, 2011). For example, if one fails to remember the name of the highest mountain peak on earth (Mt. Everest or Sagarmatha, in Nepali), this person might have an urgent and profound feeling that they can remember the mountain's name at any moment. As this example shows, two components comprise TOT experiences. The first component is the failure of memory system to recall an item (object-level component) and the second component is the metacognitive experience of imminent accessibility of the item (meta-level component; see Schwartz, 2006). Based on this, one can consider the TOT as a sign of memory failure because it shows that memory system is unable to retrieve a piece of information (D'Angelo & Humphreys, 2015; Warriner & Humphreys, 2008). One can also consider TOT as a sign of retrieval success (Cleary & Reyes, 2009), because it alerts us that the item might be accessible, and this motivates us to look further to recall the information (also see Metcalfe et al., 2017).

A main question in the study of TOT is how the metacognitive system creates the experience of the TOT. To this end, a number of theories have been proposed to explain how TOT experiences occur. In general, we can categorize the theories of TOT into two classes: the direct access theories and the heuristic–metacognitive theories of TOT (for a review, see Schwartz & Metcalfe, 2011). According to the direct-access theories of TOT, TOT is the result of subliminal processing of to-be-remembered information. According to the direct-access theories (e.g., R. Brown & McNeill, 1966; Gollan & Brown, 2006), if a to-be-remembered target induces a strong memory retrieval process, it will lead to a recall. However, if memory retrieval processes related to a to-be-remembered target is not strong enough for recall generation, but is still being activated, it may cause the experience of

TOT. That is, a processing power just below the threshold for recall, may cause TOT. Therefore, what separates a TOT experience from the experience of not-knowing the target is the presence of residual memory processes, which can present itself as retrieval of partial information.

The two-step model is an extension of direct-access theories of TOT (see Gollan & Brown, 2006), and it can explain TOT from a language production perspective. According to this model, the retrieval of lexical information happens in two steps: In step one, the cognitive system activates "the meaning-based representations", where the semantic information will be available for recall. In step two, one the other hand, the cognitive system activates "the form-based representations", where the cognitive system activates the phonological information (also Schwartz & Metcalfe, 2011). Accordingly, if a question (for example, what is the name of the gray Wizard in the Lord of The Rings trilogy?) activates the meaning-based representations (for example, "this is the wizard who helps the hobbits" or "Ian McKellen played this character in the movie adaptation") or partial phonological information, such as the name begins with a G, but not complete phonological information (Gandalf), then we experience a TOT. Therefore, according to the two-step model, a learner/speaker should be able to retrieve syntactic and semantic features but not complete phonological information of that word (see Vigliocco et al., 1997). Empirical evidence supporting the direct-access theories of TOT, especially the two-step model, mainly come from research on failure of the retrieval of lexical information. In a seminal study of TOT, R. Brown and McNeill (1966) provided participants with definitions of low frequency words and asked them to indicate if they know the target word using three categories: "know", "do not know" and "TOT." If participants were experiencing a TOT, they were instructed to guess the number of syllables and the initial letter of the missing target. Following this experiment, R. Brown and McNeill (1966) showed that participants who experienced TOTs are more likely to recall the number of syllables of missing targets as well as their initial letter. Note that in this study, participants had access to "the meaning-based representation" of the target words because they were provided with the meaning of each target word. However, they failed to completely access "the form-based representations" of the target word. Therefore, failure to access "the formed-based representation" as well as complete access to "the meaning-based representation" of the target word in this study is considered the evidence for the direct-access theories of TOT.

Following studies also supported the direct-access theories of TOT. For example, Hanley and Chapman (2008) showed that participants have more TOTs for the name of actors and actresses that contains three rather than two words (for example, Jon Bon Jovi vs. Rachel Stevens) and Vigliocco et al. (1997) showed that when experiencing a TOT, participants can retrieve grammatical gender of a target (i.e., words being described as feminine or masculine such as "stella" and "astro" as feminine or masculine words for "star" respectively), even though they could not retrieve the full phonological feature of that target.

Although there is extensive empirical support for the direct-access theories of TOT, additional studies showed that the direct-access theories cannot provide a comprehensive view of TOT. For example, Cleary (2006) tested whether increasing the familiarity of responses to general-knowledge questions, increases the possibility of experiencing TOTs. To this end, Cleary (2006) provided participants with the answer to some general-knowledge questions in the form of a word-list. Then, Cleary (2006) presented the participants with a series of questions that their answers were presented before and other questions that their answer were not presented before. Hence, in this study, participants had access to the meaning-based representations of half of the targets. However, the results showed that the rate of TOTs were similar for the questions that their answers were studied before and the questions that their answers were not presented to the participants before. According to Cleary (2006), familiarity of the answers (meaning-based representations) had not influenced the likelihood of experiencing a TOT, and other factors may indeed help to create the experience of TOT. Thus, direct-access theories of TOT may not provide us with a comprehensive explanation of TOT experiences.

The second category of theories of TOT is the heuristic–metacognitive theories (e.g., Schwartz, 2006; Schwartz & Metcalfe, 2011). According to the heuristic–metacognitive theories of TOT, the subliminal representation of the to-be-remembered target, which is proposed by the direct-access theories of TOT, is not sufficient to induce an experience of TOT. Based on these theories, TOT is the result of monitoring processes of the metacognitive system, in which the metacognitive system actively monitors the memory system and if the recall fails, it uses a number of cues[4] and clues to generates the experience of TOT. If the cues indicate that the recall is imminent, then the metacognitive system induces the experience of TOT, otherwise metacognitive system reaches the conclusion that the information is not available in the memory system. Hence, the

[4] It is important not to confuse these cues with the term cue I am using to refer to a question or information that is provided to a learner, in order for them to use to remember an item.

collection of cues that may point to the imminent possibility of retrieval of missing information are necessary for inducing a TOT.

Based on this, the nature of the cues that metacognitive system uses to generate the experience of TOT has been the topic of extensive investigation in the past couple of decades, and research indicate that metacognitive system uses the following cues among many more to generate the experience of TOT: feeling of familiarity and fluency of the cue (e.g., Cleary, 2006; Cleary et al., 2010; Metcalfe et al., 1993)), partial retrieval of target information (e.g. Koriat & Lieblich, 1974; Schwartz & Smith, 1997), emotional content of the question (e.g. Cleary, 2019; Schwartz, 2010; but see D'Angelo & Humphreys, 2012), and font characteristics of the cue (e.g. Cleary & Claxton, 2015; for a review see Schwartz & Pournaghdali, 2020).

For example, Schwartz (2010) showed that participants experienced more TOTs for the questions that had an emotional valence (e.g., "What is the word that means mercifully killing a person who is terminally ill and in great pain?") than the questions that have no emotional valence (e.g., "For which country is the rupee the monetary unit?"; but see D'Angelo & Humphreys, 2012). In accordance to Schwartz's (2010) results, Cleary (2019) showed that cues with positive valence (responds to a question or the picture of a famous person) are more likely to induce TOT experiences than those with negative valance. Moreover, Cleary (2019) showed that when participants are experiencing a TOT, they judge the unrecalled item as more positive than those unrecalled items for which they did not experience a TOT (for a review, see Schwartz & Pournaghdali, 2020). Note that emotional valence of a stimulus is neither form-based nor meaning-based representation.

Therefore, the fact that emotional valence may impact the possibility of experiencing a TOT is in contrast with the assumptions of direct-access theories of TOT.

In addition to emotional valence of the cues, several studies have shown that the feeling of fluency and familiarity of the cue may increase the possibility of experiencing a TOT. For example, in R. Brown and McNeill's (1966) study, I argue that the increase in experiencing a TOT is because of the increase in the feeling of fluency of the cue as the results of recollection of the number of syllables and the initial letter of the missing targets. Supporting the role of feeling of familiarity, for example, Cleary et al. (2010) showed that when participants are experiencing a TOT, they are more likely to report a high level of familiarity for the cue. At the beginning of this study, participants studied a series of 20 odors' name (such as incense). In one condition participants were also presented with a sticker of odor along with each odor's name and in the second condition, participants had to imagine the odor related to the name. In the testing phase of this study, Cleary et al. (2010) presented participants with a series of 40 stickers of odors (20 odors presented in the study phase and 20 new odors) and asked them to recall the name of each odor. If recalled failed, participants had to do three tasks, to indicate if they are experiencing a TOT, to indicate if they think the odor was presented to them before, and to do a memory recognition task. Results showed that prior encounter to the odor or the name had no influence on the likelihood of experiencing a TOT contrasting the predictions of the direct-view theories of TOT. However, for the odors that participants reported having TOTs for, they also reported that they have studied them at the first stage of the experiment, even if they did not. This means that participants' experience of TOTs and their feeling of familiarity for those items were intermingled. In a different study, Cleary and Claxton

(2015) showed that when participants experiencing a TOT for a word, they are more likely to report that the word's font was darker, larger, and clearer, which are some indicators of fluency. Note that in both Cleary et al. (2010) and Cleary and Claxton (2015), the actual characteristics of the cue had no influence on the probability of experiencing a TOT, but it was the subjective and inferential feeling of fluency that was accompanied a TOT experience (also see Schwartz & Jemstedt, 2021; Schwartz & Metcalfe, 2014).

In summary, it seems that the heuristic–metacognitive theories of TOT provide a better explanation for TOTs. I assert this conclusion because of both theoretical and empirical considerations. First, the possibility of subliminal processing of missing information requires more rigid empirical findings. To this date, the majority of evidence in the favor of subliminal cognitive functions are based on the methods that are refutable. For example, Shanks (2017) showed that some subliminal effects are because of statistical artifacts that are the results of post-hoc selection of trials as subliminal and supraliminal. Moreover, according to Pournaghdali and Schwartz (2020), to establish a subliminal information processing, one has to utilize a rigid measure of awareness. On the other hand, because TOTs are considered as conscious metacognitive experiences (see Schwartz & Pournaghdali, 2016), it is not clear how we can assess subliminal processing in the presence of a conscious experience. Second, empirical findings that the different cues such as feeling of familiarity of the question and emotional valence of information may be associated with experiencing TOTs is not compatible with the direct-access theories of TOT, especially because such cues are experienced consciously. Therefore, it seems the heuristic–metacognitive theories of TOT provide a better explanation regarding the origin of TOT than the direct-access theories.

From the cognitive neuroscience standpoint, the neurocomputational bases of TOT is a topic of interest. But, the research on the neural bases of TOT experiences includes only a handful of studies have explored the neural underpinnings of TOT using neuroimaging and electroencephalography techniques. These studies, however, provide us with a roadmap for future investigations on the neurocomputational mechanisms that induce the experience of TOT. In the first study that evaluated the neural bases of TOT, Maril et al. (2001) used functional magnetic resonance imaging (fMRI) to compare the neural responses between the trials that participants reported having a TOT (TOT trials) and the trials that participants reported knowing (know trials) or not-knowing (do-not-know trials) in a semantic memory task. The results indicated TOT specific responses in the anterior cingulate cortex (ACC), the right middle frontal cortex (right MFC[5]) and the right inferior frontal cortex (right IFC).

In a follow up study, Maril et al. (2005) asked participants to indicate their level of memory retrieval in a semantic memory task based on the following categories: know, do-not-know, TOT and feeling of knowing. In addition, Maril et al. (2005) recorded participants' fMRI responses in each trail. Comparing fMRI responses in the TOT trials with the other types of trials revealed TOT specific responses in the ACC, right IFC, right dorsolateral prefrontal cortex (right DLPFC) and bilateral anterior frontal cortex[6]. More

[5] Maril et al. (2005)state that this area was actually dorsolateral prefrontal cortex. This should not be surprising because dorsolateral and middle frontal cortices are adjacent areas and it is quite possible that Maril et al. (2001) actually observed dorsolateral activities.

[6] It is important to note that this study also found activities in the posterior medial parietal cortex, bilateral lateral parietal cortex, and bilateral superior PFC that was unique to both TOT and feeling of knowing trials. These findings may indicate that activities in these areas are neural bases of metacognition regardless of the type of metacognitive judgments and experiences. I will discuss this later in this study.

recently, Huijbers et al. (2017) used fMRI to examine the neural bases of successful recall, TOT, feeling-of-knowing and not-remembering when using a famous face's name as a target in older adults (age 63 to 90). In this study, TOT specific activities were observed in the lateral prefrontal cortex (LPFC), the anterior insula and the ACC. Moreover, in comparison to successful recall, TOT was associated with a similar level of activities in the hippocampus, weaker activities in the retrosplenial cortex and stronger activities in the LPFC. Additionally, in comparison to feeling-of-knowing and not-remembering responses, TOT was associated with stronger activities in the hippocampus, the retrosplenial cortex (only compared to feeling-of-knowing) and the LPFC.

Moreover, a structural MRI study examined the correlation between gray matter atrophy in different brain areas and frequency of TOT in older adults. In this study, Shafto et al. (2007) found a correlation between gray matter atrophy in the insula and frequency of TOT, in a way that as insula atrophy increased, participants experienced TOT more often. Therefore, it seems possible that insula is involved in creating TOT experiences. However, Schwartz and Díaz (2014) stated that insula is related to inaccessibility of item in the memory system and not the metacognitive experience of TOT. Hence, the results of neuroimaging studies of TOT indicate that different frontal areas including (D)LPFC, MFC, ACC, and IFC might be responsible for creating the metacognitive experience of TOT and the insula might be responsible for failure of memory system to recall the target. Future studies of TOT ought to investigate these associations more systematically.

Feeling-of-knowing

Feeling-of-knowing judgments (FOK or FOKs) are metacognitive judgments about the likelihood of correct retrieval of an item in the future, when they are not recallable at the moment (Hart, 1965; Koriat, 2000; Metcalfe, 1986)[7]. For example, when I cannot retrieve the name of the tallest mountain peak in North America, I can predict if I will recognize the name of the mountain from a list of several tall mountains[8]. FOK judgments, which are collected when participants cannot recall an item, are similar to TOT judgments but are different from them in a number of interesting ways. First, TOTs are involuntary and spontaneous experiences and are not subject to the participants conscious decision to produce them. To induce an FOK judgment, however, participants must voluntarily use their metacognition to examine the content of their memory to produce the FOK judgments. That is, TOTs are involuntary but FOKs are voluntary experiences (see A. Brown, 1991). Second, FOK may be analytical, that is, based on reasoning, whereas TOTs arise from a feeling of imminence, regardless of the cognitive mechanism that produces it. Finally, FOKs may lack the urgent feeling of accessibility of the unrecalled item that typically occurs with TOTs. Therefore, the presence or absence of the urgent feeling of accessibility might be the differentiator of TOTs from FOKs[9].

---

[7] Although FOKs are usually collected for the unrecalled items, some researchers also ask participants to provide FOK judgments for the items that they recall them (see Schwartz et al., 2016). The decision to collect FOK judgments for unrecalled items or for unrecalled and recalled items depends on the questions asked in a study. I will not discuss this point further because it is beyond the scope of this study.

[8] Mt. Elbrus is the tallest mountain in Europe and Mt. McKinley/Denali is the tallest mountain in North America.

[9] Because of the differences between TOT and FOK, I consider these two as different metacognitive judgments. However, an interesting empirical question is whether TOTs and FOKs share a common or different neurocognitive mechanism (e.g., see Metcalfe et al., 1993; Schwartz, 2008). This issue is part of a more general issue in metacognition research: whether all of the metacognitive experiences have a common neurocognitive mechanism or each is based on a different unique mechanism[9] (see Vaccaro & Fleming, 2018). I will discuss this interesting question later in this study.

An interesting question regarding FOK is how metacognitive system creates FOK judgments. Several theories were postulated during the past few decades to explain how the metacognitive system creates FOK judgments. We can categorize such theories into three different classes, similar to those discussed with respect to TOTs: the direct-access view (Hart, 1965; also see Koriat, 2000; Schwartz, 1994), the accessibility hypothesis (Koriat, 1993, 1995) and the cue familiarity hypothesis (Metcalfe et al., 1993).

According to the direct-access view, FOK is the output of the system that has direct access to the memory storage and becomes active in situations when recall fails (Hart, 1965). That is, when memory recall fails, the metacognitive system monitors the existence of the missing information in the memory storage. If this system reaches the conclusion that there is a trace of missing information in the memory storage, then it creates a high FOK experience. Otherwise, the system creates a low FOK experience. According to the direct-access view, because this system has direct access to the memory storage, it should have access to the correct information stored in the memory system, and therefore, its prediction (FOK judgments) should be always accurate. This, however, is not the case. That is, FOK judgments might be based on inaccurate information (see Koriat, 2000) and the predictions of FOK judgments are not always accurate. Therefore, the direct-access view fails to explain why FOKs may make inaccurate prediction[10].

The direct-access view assumes that the monitoring system that observes the trace of information in the memory system has direct access to the memory storage. This

---

[10] It is important to note that the direct-access view has been abandoned in favor of other theories of FOK. Therefore, this view is no longer a viable theory of FOK.

assumption is in contrast with other classes of FOK theories, which consider an FOK as a result of inferential computations based on a number of cues and clues. For example, the accessibility hypothesis (Koriat, 1993, 1995) formalizes FOKs as experiences resulting from inferential computations based on retrieval of partial information of the to-be-remembered item. Hence, FOK is the result of partial recall of the to-be-remembered item (see Koriat, 2000). For example, when asking a participant about the tallest mountain peak in Europe (Mt. Elbrus), the participant may remember that this mountain peak starts with the letter "E" and is made up of six letters. According to this theory, the metacognitive system uses the accessible partial information to make an inference about the possibility of correct retrieval of the to-be-remembered item and, in this way, it creates the FOK judgments. Moreover, the accessibility hypothesis postulates that metacognitive system cannot monitor the accuracy of the partial information. Therefore, this hypothesis assumes that the accuracy of the recalled partial items is irrelevant for inducing FOK judgments. That is, the accuracy of the recalled partial items is not accessible to the system that induces FOK judgments. However, the accessibility hypothesis predicts that the accuracy of the recalled details may influence the metacognitive sensitivity of FOK judgments (Koriat, 1993).

Empirical evidence supports the accessibility hypothesis. Early evidence for the accessibility hypothesis came from the Koriat' (1993) study. In this study, Koriat (1993) asked participants to memorize a list of consonant strings with 4 elements (letters) each (for example, FKDR). After that, participants were asked to recall each string completely or partially, to indicate their FOK using a 0 to 100 scale, and to perform an 8-alternative forced-choice recognition task. According to the results, when participants recalled more partial information, they were more likely to report a high level of FOK. On the other hand, when participants recalled no partial information or one element of the string, they were more likely to report a low level of FOK. According to Koriat, the accuracy of the partially recalled information did not influence the magnitude of FOK judgments, but it influenced the metacognitive sensitivity of FOK, that is, when partial information was correct, recognition was more likely to be correct as well.

Koriat (1995) reported similar results when assessing FOKs for semantic memory in the form of general-knowledge questions. In this study, Koriat (1995) asked participants to recall the answers to a set of general-knowledge question, to indicate the level of FOK for each question, and finally to perform a recognition task. According to this study, the amount of partially accessible information predicted the magnitude of the FOK judgments and the accuracy of such information enhanced the metacognitive sensitivity of the FOK judgments.

Hence, the results of many studies supported the accessibility hypothesis and indicated that the accessibility of partial information indeed increases the magnitude of FOK judgments (e.g., Koriat, 1993, 1995). Moreover, some researchers have expanded this hypothesis and asserted that accessibility of noncriterial and contextual information that are not directly part of the to-be-remembered target may also influence the magnitude of FOK judgments (e.g., Brewer et al., 2010) For example, Brewer et al. (2010) proposed that recollection of noncriterial information may indeed increase the magnitude of FOK judgments. In this study, Brewer et al. (2010) presented participants with a series of 80 pictures and for each picture a male or a female voice provided the verbal label for each picture. In this experiment, participants were instructed that the main task is to memorize the pictures and not pay attention to the gender of the speaker. After this phase, participants were presented with an unexpected test in which they were presented with the picture and for each picture, they had to indicate if the speaker who mentioned the label of that picture was a male, female or if they did not know (remember) the gender of the speaker. If a participant indicated "don't know" response for a picture, they were asked to indicate their FOK for recognizing the speaker's gender of that verbal label if they were presented with the spoken word again. The results of this study indicated that correct recollection of noncriterial information (the label of the picture) influences the magnitude of FOK judgments about the critical information (the gender of the speaker).

In addition, Schwartz et al. (2014) also showed that the amount of contextual (noncriterial) information increases the magnitude of FOK judgments. In this study, Schwartz et al. (2014), presented participants with a series of images of made-up animals and their made-up names. In one condition, the only information provided to the participants was the name of the animal. In the second condition, participants were presented with the name and one item of contextual information (country), and in the third condition, participants were presented with the name and three items of contextual information (country, weight and diet; see Schwartz et al., 2014, Figure 1). In accordance with the accessibility hypothesis of FOK, participants reported higher FOK in the second and third condition than the first condition. In addition, retrieval of contextual information resulted in report of higher FOK judgments. Therefore, the results of Brewer et al. (2010) and Schwartz et al. (2014) both supported the idea that partial retrieval of information that are not directly related the to-be-remembered target are also influential in creating FOK judgments (also see Hanczakowski et al., 2017). In summary, the empirical results support the accessibility hypothesis of FOK.

Finally, the third class of theories of FOK is the cue familiarity hypothesis (Metcalfe, 1993; Metcalfe et al., 1993). According to the cue familiarity hypothesis, an FOK judgment is based, at least partially, on the familiarity of the cue. For example, when asking about the tallest mountain peak on earth, one can have a sense of familiarity of this mountain because they have seen documentaries about it before or they have a friend who climbed this mountain peak. Therefore, this theory suggests that the feeling of familiarity of the cue is essential for inducing FOK judgments.

Critical to testing this account is manipulating the familiarity of the cue. This can be achieved by the mean of priming, and some studies have manipulated the familiarity of the cue using a priming procedure. In such studies, half of the cues are presented in a pre-testing/pre-learning priming phase, and half of the cues are only presented during the learning/testing phase. From this, we can assume that those cues presented in the priming phase are more familiar for participants than the cues that were only presented in the learning/testing phase. Accordingly, if the primed cues result in higher levels of FOK than non-primed cues, we can take the results as evidence for the cue familiarity account of FOK.

Using this logic, some studies have tested and found evidence for the cue familiarity account of FOK. For example, in a paired-associate learning study, Schwartz and Metcalfe (1992) showed that the cues that were presented in a pre-test priming phase induced higher FOK judgments than cues that were not presented in a pre-test priming phase. Metcalfe et al. (1993) used a slightly different strategy to test the cue familiarity account of FOK. In this study, Metcalfe et al. (1993) asked participants to memorize word-pairs (AB), with the first element of a pair was a cue (A) and the second element was a target (B). The learning phase of this study had two parts. In the first part, participants learned the association between two pairs (AB). Metcalfe et al. (1993) however manipulated the pairs in the second part in a way that it created four condition in relation to the first phase: the same pair was repeated again (AB-AB), the same cue was repeated with a different but similar target (AB-AB′), the same cue was repeated with a different but unsimilar target (AB-AD) and a new cue with a new target (AB-CD). Metcalfe et al. (1993) argued that if the cue familiarity is indeed the source of FOK, there should not be a difference between conditions with repeating cue (AB-AB, AB-AB′, AB-AD) and they should all have higher FOK than the pair with a new cue (AB-CD). The results of this study supported this assumption: FOK magnitude was higher in the condition with repeating cue than the condition with a new cue. However, there was no significant difference between three conditions with repeating cues (see Metcalfe et al., 1993, Figures 1 and 2). Therefore, cue familiarity account of FOK is also supported by the empirical studies.

It is important to note that the cue familiarity and the accessibility accounts of FOK are not mutually exclusive and they share an assumption: both accounts assume that FOK judgment are not based on the direct access to the trace of memory system, but are the results of inferential computations based on a number of cues and clues (see Koriat & Levy-Sadot, 2001). Moreover, it seems that these two theories most likely explain different stages of metacognitive processes that result in the generation of FOK judgments (Koriat & Levy-Sadot, 2001). That is, cue familiarity and partial accessibility are two interactive stages of FOKs. Based on this idea, cue familiarity initiates a feeling of familiarity and therefore a feeling that the to-be-remembered target may be actually known by the learner. If the feeling of familiarity is strong enough, it initiates a search for the missing information. In such situation, if parts of missing information or contextual information relating to the target are retrieved by the learner, a stronger FOK will be induced. Therefore, a strong feeling of familiarity is a prerequisite to a FOK judgment and in the absence of strong feeling of familiarity, the presence of partial target information may not trigger a strong FOK. In conclusion, the cue familiarity and the accessibility hypotheses of FOK are two interactive theories that can provide us with a clear picture regarding the nature of FOK judgments.

The neurocomputational bases of FOK is a topic of interest from a cognitive neuroscience standpoint, and it has been studied using neuroimaging techniques. Studies that have evaluated the neural based of FOK, point to brain activities in several regions of interest (ROIs) as the neural bases of FOK. The brain regions that have been reported as the ROIs for FOK include the middle and the inferior frontal areas, the ACC, the medial temporal lobe and parietal areas.

For example, Kikyo et al. (2002) reported a positive correlation between the magnitude of FOK for general-knowledge questions and the strength of fMRI signals from the right inferior frontal gyrus (IFG) and a subset of the left IFG. This indicates that the right IFG and subset of the left IFG may be involved exclusively in inducing the FOK judgments and may have no involvement in signaling the recall state. In addition, Kikyo et al. (2002) found a positive correlation between the magnitude of FOK for the general-knowledge questions and strength of fMRI signals from parts of the left IFG, the ACC, the left middle frontal gyrus (MFG), and bilateral caudate nucleus that were also present for the recalled items. This means that these areas may be involved in creating FOK experiences by signaling the metacognitive system that memory system has failed to recall an item.

In a follow up study, Kikyo and Miyashita (2004) evaluated the neural bases of FOK for famous faces and found fMRI responses that correlated with the magnitude of FOK judgments in many frontal and temporal regions including the IFG, the MFG, the ACC, the Insula, the superior temporal sulcus (STS), superior temporal gyrus (STG), middle temporal gyrus (MTG). Moreover, Maril et al. (2003) compared the brain responses to three recall conditions: know, do-not-know, FOK and found graded pattern of response in the left IFC, left MFC, left dorsal frontal cortex, left parietal cortex and the ACC, with the strongest response in the “know” trials, the weakest response in the “do-not-know” trials and response in the “FOK” trials between the other conditions. Moreover, Maril et al. (2003) found that the neural responses in a part of left MFC was comparable between “know” and “FOK” trials. Such responses were weaker in the “do-not-know” condition. In a follow up study, Maril et al. (2005) compared fMRI signals in the trials that participants indicated their level of level of memory retrieval in a semantic memory task based on the following categories: know, do-not-know, TOT and FOK. Maril et al. (2005) found activities in the posterior medial parietal cortex, bilateral lateral parietal cortex, and bilateral superior PFC that was unique to both TOT and FOK trials. These findings may indicate that TOT and FOK are originating from the same neurocomputational mechanisms, but further investigation is needed to explore this possibility. Finally, Schnyer et al. (2005) found FOK related activities in the MFC, the ACC and ventromedial prefrontal cortex (VMPFC).

In summary, these studies pointed to several brain regions as the potential neural bases of FOK. FOK related activities in the IFC, the MFC, and the ACC have been reported across the studies. FOK related activities in other regions, however, were only reported in one or two studies. Some of these areas include: caudate nucleus, the insula, the STS, the STG, the MTG, dorsal frontal cortex and lateral parietal cortex. Because the association between magnitude of FOK and the magnitude of fMRI signals from the IFC, the MFC and the ACC have been reported, we can conclude that these areas are the prime candidates for investigating the neural bases of FOK. One can ask if the neural bases of FOK depends on the type of memory information that a FOK judgment is evaluating (for example, semantic, episodic, and procedural memory). For example, is it possible that the FOK for semantic memory is based on different neural activities than the FOK for episodic memory?

A subsequent fMRI study shed more light on this question. In this study, Reggev et al. (2011) compared the neural bases of semantic and episodic FOK (i.e., FOK for semantic memory and episodic memory), and found preferential activities in the right IFC for semantic FOK. Episodic FOK, on the other hand, was associated with the activities in the left MTG, the cuneus, and the posterior cingulate cortex. Elman et al. (2012) also compared fMRI correlates of semantic and episodic FOK and found stronger episodic FOK activations in the left ventral posterior parietal cortex, precuneus, and frontal pole. Elman et al. (2012), however, found stronger semantic FOK activations in the right anterior temporal lobe. Hence, these results confirm the assumption that the neural bases of FOK depends on the type of memory information that a FOK judgment is evaluating.

Post-decision Confidence

Confidence judgments are retrospective metacognitive judgments that estimate the precision of our cognitive and perceptual decisions (e.g., visual decision; see Grimaldi et al., 2015; Mamassian, 2016). For example, if I retrieve that Tenzing Norgay was the first person of Sherpa heritage to reach the summit of Mt. Everest, I can judge the confidence that I am correct. Most of the research on confidence originate from studies of perceptual decision making, and only a handful of studies systematically evaluated confidence in regard to metamemory[11]. For this reason, in the rest of this section, I will mainly discuss confidence in regards to perceptual decision making (or perceptual confidence), but my discussion of confidence is also related to confidence in regard to memorial decisions.

The exact mechanism(s) by which metacognitive system makes the confidence estimations is matter of extensive research and many computational models have attempted to explain the mechanism(s) of confidence (e.g., Green & Swets, 1966; Maniscalco et al., 2021; Maniscalco & Lau, 2016; Pleskac & Busemeyer, 2010; Ratcliff & Starns, 2009; Shekhar & Rahnev, 2021a). A comprehensive discussion of all of these models is beyond the scope of this study. Thus, I will only focus on some prominent classes of models of confidence that are extensively investigated.

The first class of models of confidence is the signal detection theory-based (SDT-based) models of confidence (Green & Swets, 1966). To discuss these SDT-based models, it is important to understand how SDT quantifies perceptual (object-level) decisions.

---

[11] The only exception is study of metamemory in legal psychology where confidence judgments of eyewitnesses is a hot topic.

According to SDT (Green & Swets, 1966; Macmillan & Creelman, 2005), internal representation of a stimulus is probabilistic and varies from one trial to the next. For example, when we present a happy face to a participant several times, its internal representation varies across different trials. Accordingly, a probability distribution represents the variations in the internal representation of a stimulus across different trials. According to SDT, if we present a participant with one of two stimuli that are different from each other, along one perceptual dimension (for example happy and sad faces that are different from each other along the dimension of facial expression), a unique probability distribution represents variations in the internal representation of each of these two stimuli across trials along this dimension (see Fig. 2a). For example, a probability distribution represents the variations in the internal representation of a happy face along the dimension of facial expression and a probability distribution represents the variations in the internal representation of a sad face along the dimension of facial expression.

In this case, the amount of overlap between the two distributions along the dimension of interest and consequently the distance between the mean of the two distributions is an index for the ability of a perceptual system to discriminate the internal representations of these two types of stimuli (McNicol, 2005). Accordingly, a complete separation between the two distributions means that a perceptual system can completely discriminate the internal representation of these two stimuli. On the other hand, as the amount of overlap between two distributions increases, a perceptual system losses its ability to discriminate the internal representations of these two stimuli. In SDT terminology, the ability of a perceptual system to discriminate the internal representations of two stimulus categories is called sensitivity.

Moreover, an observer places a decision bound along the dimension of interest to classify the category of a stimulus. If the insensitivity of the internal representation of a stimulus exceeds the decision bound, a participant classifies the stimulus as a category that has the higher mean and if the insensitivity of the internal representation of a stimulus does not exceed the decision bound, this participant classifies the stimulus as a category that has the lower mean. For example, to classify a face as a happy or sad face, participants place a decision bound along the dimension of facial expression in which the happy face has a lower mean than the sad face. In this case, when presenting a happy or a sad face to the observer, if the intensity of the internal representation of the face exceeds the decision bound, then the observer reports the face as a sad face. Otherwise, the observer reports the face as a happy face. In SDT terminology, the decision bound is called criterion or bias.

According to the SDT-based models of confidence, perceptual decisions and confidence judgments derive from the same latent evidence (Green & Swets, 1966). That is, the distance between a single internal representation (the sensory evidence) from the observer's criterion determines the level of confidence in the decision (see Fig. 2a). For example, if we present a sad face and the internal representation of this presentation is away from the criterion in any direction, then the observer makes a high confidence judgment on their perceptual decision. On the other hand, if the internal representation of this presentation is relatively close to the criterion in any direction, then the observer makes a low confidence judgment on their perceptual decision (see Galvin et al., 2003; Mamassian, 2016).

In general, SDT provides a good account of the accordance between object-level accuracy and the level of confidence. However, it fails to explain how the level of confidence may be associated to response time (see Kiani et al., 2014; Pleskac & Busemeyer, 2010). Different studies have shown that faster responses are usually accompanied by higher level of confidence (e.g., Kiani et al., 2014). That is, there is a positive correlation between response time and confidence, and SDT fails to account for this association. Hence, to account for this association, we need to use a different class of models of confidence.

To explain how confidence and response time are related we use the drift diffusion models (DDM; Ratcliff & Starns, 2009) of confidence. Similar to SDT, it is important to understand how DDM quantifies perceptual decisions. To this end, we can start by examining a hypothetical experiment. In each trial of this experiment, we present a face that is either happy or sad, and participants task is to report the emotional category of each face as fast and accurately as possible. According to DDM (Ratcliff, 2002; Ratcliff & McKoon, 2008), perceptual decisions are the results of a noisy process that gradually accumulates perceptual evidence towards one of the two opposing decision or response criteria, each corresponding to a perceptual decision (for example, happy vs. sad, see Fig. 2b). This process starts from the onset of stimulus until perceptual evidence reaches a decision criterion. In our hypothetical experiment, from the onset of a face, accumulation of evidence in the favor of one of the two face categories (happy vs. sad) starts and it will be terminated as soon as it reaches a decision criterion for happy or sad face.

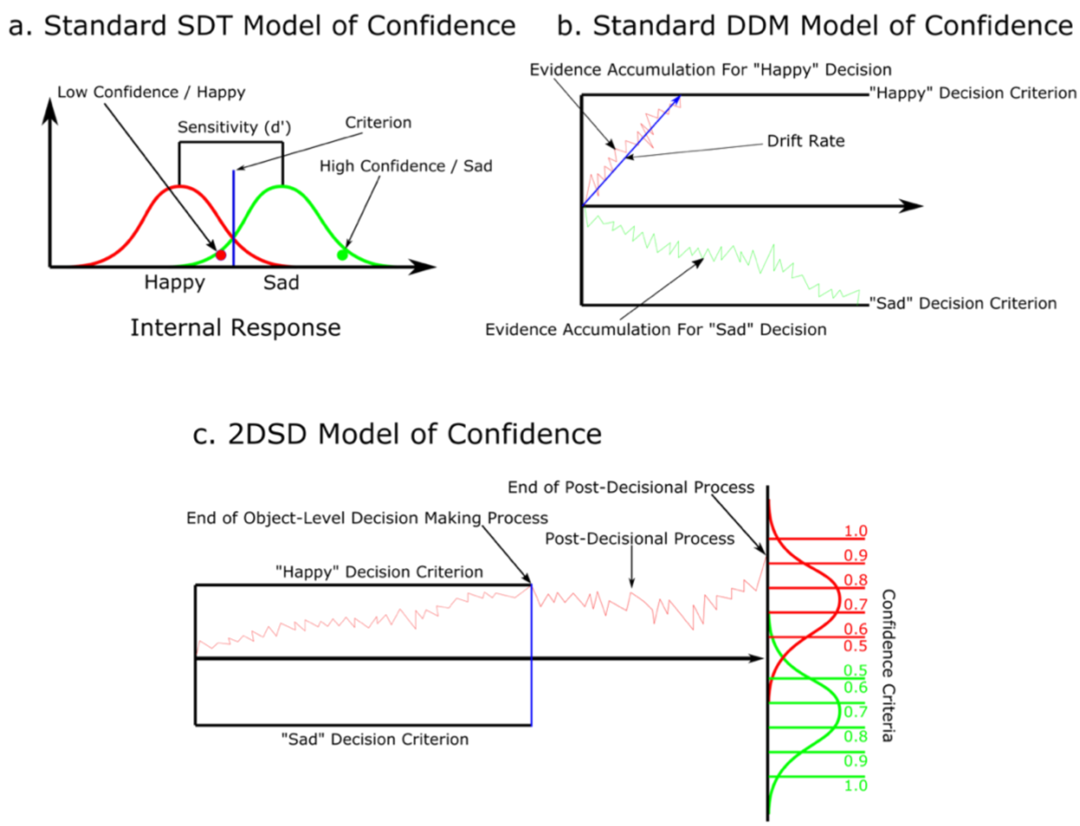

Fig. 2 Computational Models of Confidence. (a). According to the SDT model of confidence (Green & Swets, 1966), the distance between a single internal representation (the sensory evidence) from the observer's criterion determines the level of confidence in the decision. In this figure, the red dot represents a single internal representation. Because the internal representation is below the criterion, participant reports perceiving a "happy face" and because the internal representation is close to the criterion, participant reports a low level of confidence. The green dot, on the other hand, is an internal representation that is beyond and away from the criterions. Hence, participant reports perceiving "sad face" with high confidence for this internal representation. (b). According to the DDM model of confidence, the drift rate determines response time as well as the level of confidence. In this graph, the red drift has a large slope. Hence, it has a high drift rate. This means that participant has a faster perceptual decision ("happy face") with a higher confidence rating. The green drift has a smaller slope. Hence, it has a low drift rate. This means that participant has a slower perceptual decision ("sad face") with a lower confidence rating. (c). According to the 2DSD model of confidence, confidence decisions happen as the result of a post-decisional processing that determines the likelihood of correctness of the decision. According to 2DSS, there are several gradual bounds, each determining confidence rating related to the object-level decision (horizontal lines in the figure). Accordingly, the location of drift at the stoppage time determines the confidence of a decision maker on the accuracy of their decision. In this graph, the post-decisional process passes the criteria for probability of 90 percent for "happy face" perceptual decision. Therefore, participant reports a 90 percent probability that their decision is correct (i.e., confidence rating of 9 out of 10).

According to DDM (Ratcliff, 2002; Ratcliff & McKoon, 2008), the quality of perceptual evidence determines the rate of accumulation of evidence. In DDM terminology, the rate of accumulation of evidence is called drift rate. Accordingly, the difficulty or easiness of a perceptual task is determined by the value of drift rate. A high drift rate represents an easy perceptual task, and a low drift rate represents a difficult perceptual task. Hence, a high drift rate means a faster response time than a low drift rate. For example, if happy and sad faces are quite different from each other, the drift rate would be higher, which results in a fast response. On the other hand, if happy and sad faces are quite similar to each other, the drift rate would be lower, which results in a slow response. Finally, a drift rate might be positive or negative, representing the direction of the drift toward one of the criteria. For example, a negative drift rate may indicate the direction of the drift toward the happy face and positive drift rate may indicate the direction of the drift toward the sad face. Finally, DDM assumes that there is within-trial variability, and therefore, the drift rate varies from one trial to the next. Consequently, the response time varies from one trial to the next. For example, even if we present a face that is clearly a happy face several times, a participant has different response times.

DDM account of confidence has similar assumption as SDT: perceptual decisions and confidence judgments derive from the same latent evidence. Accordingly, the drift rate, not only determines that response time, but also the level of confidence (Kiani et al., 2014; Ratcliff & Starns, 2009). That is, a higher drift rate (i.e., faster response) corresponds to a higher level of confidence judgment, and a lower drift rate (i.e., slower response) corresponds to a lower level of confidence judgment. Hence, DDM provides a good account of positive correlation between response time and confidence.

Hence, SDT and DDM can explain association between different aspects of object-level decisions (accuracy and response time) and confidence. However, both of these models are based on the assumption that object-level decisions and confidence derive from the same latent evidence. Therefore, they predict that there is always a complete correspondence between accuracy and response time on one hand, and confidence on the other hand (Green & Swets, 1966; Kiani et al., 2014; Sanders et al., 2016). However, research show that confidence and object-level decisions are not always congruent, and there are many cases of dissociations between object-level decisions and confidence (see Maniscalco et al., 2021).

For example, Lau and Passingham (2006) used metacontrast masking to manipulate visibility of target stimuli (diamond vs. square) and asked participants to classify the shape of target stimuli using a discrimination task (diamond vs. square) and to rate their confidence on their discrimination performance. Critically by manipulating stimulus onset asynchrony (SOA), Lau and Passingham (2006) created two different conditions in a way that participants perceptual discrimination performance was diminished similarly in comparison to the visible condition. However, the results showed that confidence level was diminished in one condition more than the second condition. These results indicate that there is a dissociation between level of confidence and object-level performance. Further results also support this conclusion. For example, applying TMS on frontal cortex diminished only confidence and not object-level performance (e.g., Rounis et al., 2010). Therefore, a model of confidence should be able to explain the dissociation between object-level decisions and confidence judgments. Critically, such model should be biologically plausible.

As I mentioned, the DDM and SDT assumption that object-level decisions and confidence derive from the same latent evidence, is in contrast to the empirical evidence.

For this reason, more recent SDT-based and DDM-based models of confidence proposed that confidence may require additional computations which are based on different parts of neurocognitive system (for example, see Maniscalco & Lau, 2016). For example, Pleskac and Busemeyer (2010) proposed the two-stage dynamic signal detection (2DSD) model of confidence (see Fig. 2c). 2DSD models response time similar to DDM. That is, the drift rate determines the response time. However, 2DSD postulates that after drift reaches the decision criterion, a secondary process (post-decisional processing) starts that accumulates evidence to determine the likelihood of correctness of the decision, and this takes a finite and fixed amount of time to complete. To this end, there are several gradual bounds, each determining a likelihood for the decision to be correct (horizontal lines in Fig. 3c). Accordingly, the drift may pass some of these bounds and reaches a bound by the stoppage time. Hence, the location of drift at the stoppage time determines the confidence of a decision maker on the accuracy of their decision.

Although 2DSD seems to provides a better account of confidence judgments than SDT and DDM, it is not the only model that assumes different computations for object-level and confidence decisions. Over the years, many other models of confidence have been proposed that are based on DDM or SDT but with additional computational mechanism(s) for confidence judgments. Still, 2DSD and most of these models assume that participants' confidence judgments are optimal with no error (e.g., Pouget et al., 2016; Sanders et al., 2016). Therefore, they fail to provide either a behaviorally valid or a biologically plausible account of the dissociation between object-level decisions and confidence judgments.

However, a recent model that seems to provide a biologically plausible explanation of the dissociation between confidence and object-level decisions is the differential tuned inhibition (DTI) model (Maniscalco et al., 2021). DTI is based on a known property of a perceptual (visual) system: tuned inhibition (or tuned normalization), which is defined as the inhibition of a neuron with a specific tuning function by other neighboring neurons with opposing tuning functions (e.g., see Ni et al., 2012). DTI is also based on a known property of confidence decisions: in order to make a confidence judgment, a metacognitive system ignores the evidence against an object-level decision and only weights the evidence that are in favor of an object-level decision (e.g., see Peters et al., 2017). Based on this, DTI assumes that the degree of tuned inhibition of a neuron determined if that neuron processes perceptual vs. confidence information. “Strongly inhibited differencing” neurons evaluate the balance of perceptual evidence for different perceptual decisions. Hence, they are involved in making a perceptual decision. “Less inhibited evidence accumulation” neurons encode and wight evidence in favor of a perceptual decision and ignore evidence for the opposing decision. For example, they encode and weight evidence in favor of rightward motion and ignore the evidence in favor of leftward motion. Hence, “less inhibited evidence accumulation” neurons are involved in making confidence decisions.

Accordingly, DTI consolidate these two types of neurons into a dynamic evidence accumulation network that determines perceptual and confidence decisions. Following is the description of the architecture of this dynamic network: accumulator unites (or neurons) at the first stage of this network are tuned to various stimulus alternatives, and they accumulate stimulus evidence at any moment. They then send inhibitory or excitatory inputs toward the second stage of the network. In this stage, “strongly inhibited differencing” neurons weight the input from the unties with opposing tuning functions against each other. When a “strongly inhibited differencing” neuron with a specific tuning function reaches a threshold level of evidence, an object-level decision is made.

After an object-level decision, “the less inhibited evidence accumulation” neurons compare the activity of accumulator unit for the chosen stimulus against a set of thresholds for different confidence ratings. The result of this process is a confidence judgment. According to DTI, the duration of post-decision processes determines the capability of a confidence judgment in evaluating the object-level decision (i.e., metacognitive sensitivity of confidence). Based on this, longer post-decision processes result in higher metacognitive sensitivity of confidence (also see Yu et al., 2015). In summary, DTI can explain the dissociation between confidence and object-level performance by implementing differences in the degree of tuned inhibition of a neuron. Consequently, DTI does not consider confidence judgments to be optimal, even though it can explain how optimal confidence judgments may arise. However, future studies should test different predictions of this model.

From cognitive neuroscience standpoint, the neurocomputational bases of confidence is a topic of interest. Studies that evaluate the neural bases of confidence judgments usually follow one of the two related goals: to evaluate the neural bases of confidence judgments or to evaluate the neural bases of metacognitive sensitivity of confidence judgments. Critical to both lines of research, is an accurate dissociation between confidence-related and object-level related brain activities. Without such dissociation, it is impossible to evaluate the neural bases of confidence judgments, because the observed neural activities in a study of confidence might be the results of object-level processes and not confidence-related processes (e.g., Kellij et al., 2021). A strategy to achieve this dissociation is by implementing “matched performance/different-confidence” approach (Lau, 2008; Maniscalco et al., 2020). In this approach, we compare a specific feature of confidence judgment, between two conditions that have equivalent object-level performance. For example, if two conditions of a perceptual task results in an equivalent object-level performance (e.g., 80 percent discrimination accuracy) but different levels of confidence (e.g., 30 percent confidence in the first condition and 70 percent in the second condition), the we successfully utilized this approach. In this case, we can consider any differences in the brain activities between the two conditions as the neural bases of confidence judgments.

The second approach to achieve the aforementioned dissociation is to compare the neural bases of object-level and metacognitive sensitivities[12] (Fleming & Lau, 2014). If activity of a brain region is associated with metacognitive and not object-level sensitivity, then we can conclude that that area is responsible for metacognitive evaluation of object-level information. Research implementing these two strategies show that different (pre)frontal areas, especially DLPFC and anterior prefrontal cortex (aPFC) may be involved in generation and metacognitive sensitivity of confidence judgments[13].

More specifically, research show that DLPFC might be involved in generation of a confidence judgment. In an early study, Henson et al. (2000) found increases in DLPFC

---

[12] Metacognitive sensitivity of a metacognitive judgment refers to the ability of that metacognitive judgment to accurately predict precision in an object-level task. I will discuss this concept later in this study.

[13] Note that the neural bases of object-level cognition depend on the type of object-level task we are using. For example, studies point to different occipital and temporal areas as the neural bases of visual discrimination (e.g., Baizer et al., 1991; Baroni et al., 2017; Jiang et al., 2009).

activities in the trials that participants rated low confidence on their episodic memory recognition. In this study, Henson et al. (2000) presented participants with a list of 90 words in a learning phase. During the testing phase, Henson et al. (2000) presented 180 words (90 old words and 90 new words) and asked participants to indicate if each word was previously presented to them and to rate their confidence on their memory recognition task. Comparing the BOLD signals in the trials that participants reported low and high confidence showed elevated BOLD signal from DLPFC in the trials that participants reported low confidence.

Fleck et al. (2006) found a similar results. In this study, Fleck et al. (2006) asked participants to do either a memory recognition task (which was similar to Henson et al's (2000) recognition task) or a perceptual discrimination task and to rate their confidence on their performance on each tasks using a four-point scale. The results showed that DLPFC shows higher BOLD activations in the low confidence trials than in the high confidence trials. More importantly, the elevation of BOLD signals in the low confidence trials was independent of type of object-level task (memory and visual). This indicates that DLPFC involvement in confidence generation might be module-independent (see the section titled General vs. Specific Mechanisms of Metacognition). It is important to note that neither Henson et al. (2000) nor Fleck et al. (2006) used matched performance/different-confidence approach. Therefore, it is possible that object-level processes may influence the observed BOLD signals in both studies.

Further studies, however, provided evidence against this criticism. For example, by using matched performance/different-confidence approach, Lau and Passingham (2006) showed that the middle DLPFC (mid-DLPFC) is associated with the level of confidence judgments. In this study, Lau and Passingham (2006) manipulated the visibility of target stimuli using backward masking in two different conditions in a way that the object-level accuracies were equivalent across the two conditions. However, the confidence level was diminished in one condition more than the second condition. Comparing the fMRI responses between the two conditions revealed that mid-DLPFC is associated with the level of confidence judgment.

More recently, Morales et al. (2018) compared the fMRI response between the trials that participants reported their confidence on their performance in a visual discrimination memory recognition tasks. Results showed that fMRI BOLD signal from DLPFC was diminished in the trials that participants reported a high confidence level and was elevated in the trials that participants reported a low confidence level. In summary, fMRI studies of confidence show that DLPFC activities is associated with generation of confidence judgments, and this association is independent of the modality of the object-level tasks that confidence is evaluating. Whether other brain areas are also involved in generation of confidence especially for when confidence is evaluating different types of object-level tasks across different modalities is a matter of empirical investigation and further studies should focus on this question (I will discuss this issue later in the section titled General vs. Specific Mechanisms of Metacognition).

In addition to the association between DLPFC activities and confidence generation, two lines of research show an association between aPFC and metacognitive sensitivity of confidence judgments. First, studies show a direct correlation between the gray matter volume of aPFC and metacognitive sensitivity. For example, Fleming et al. (2010) showed that gray matter density in aPFC is correlated with metacognitive sensitivity of confidence judgments (measured by type-2 ROC curve). aPFC gray matter density, however, was not correlated with object-level sensitivity and the level of confidence judgment. In line with this, McCurdy et al. (2013) showed a correlation between the volume of aPFC and metacognitive sensitivity of confidence, when confidence was evaluating perceptual discrimination performance (also see Allen et al., 2017; Baird et al., 2013, 2015). In contrast, the results of this study showed no significant correlation between the volume of aPFC and metacognitive sensitivity of confidence, when confidence was evaluating memory recognition performance[14].

The results of Fleming et al. (2010) and McCurdy et al. (2013) indicate that aPFC is involved in accurate confidence evaluation of visual information. Sinanaj et al. (2015), on the other hand, expanded these results and showed that the volume of aPFC is associated with metacognitive sensitivity of confidence, when participants were asked to judge their confidence on their visuomotor performance. In this study, participants had to draw a trajectory from a starting point to a target point using a cursor. In some trials, however, the computer interfered with participants trajectory and displaced the cursor. At the end of each trial, participants had to indicate if they noticed any displacement of the cursor and to rate their confidence on their response. The results showed that participants' metacognitive sensitivity of confidence was correlated with the volume of their aPFC.

In addition to the structural neuroimaging studies, fMRI studies also support the involvement of the aPFC in metacognitive sensitivity of confidence. For example,

---

[14] I will discuss the details of McCurdy et al's (2013) results in the section titled General vs. Specific Mechanisms of Metacognition.

Yokoyama et al. (2010) found activities in aPFC is correlated with metacognitive sensitivity of confidence judgment of a memory task (measured by Gamma correlation). aPFC activities, however was uncorrelated with the memory tasks performance. In addition, Fleming et al. (2012) showed that aPFC is correlated with metacognitive sensitivity of confidence judgment of a visual discrimination of face from house stimuli (measured by type 2 receiver operating characteristic).

In addition to aPFC and DLPFC, other areas may also be involved in creation and metacognitive sensitivity of confidence. These areas include the ACC (Fleming et al., 2012; Morales et al., 2018; Yokoyama et al., 2010), precuneus (McCurdy et al., 2013; Morales et al., 2018), STG (Yokoyama et al., 2010), postcentral gyrus (Yokoyama et al., 2010), inferior parietal cortex (Yokoyama et al., 2010), the insula (Morales et al., 2018; Sinanaj et al., 2015; Yokoyama et al., 2010), inferior temporal gyrus (Fleming et al., 2010), and the hippocampus (Allen et al., 2017). Because confidence-related activities of these neural areas were reported only in so few studies, I will not discuss them later. But it is worth noting that different object-level tasks used across studies may be the reason for these diverse findings. For example, it is quite possible that we can see confidence-related activities in precuneus only when participants have to rate their confidence on their memory recognition accuracy. Based on this, future research should evaluate the involvement of each of these areas in different aspects of confidence evaluation of varieties of object-level tasks.

Major Questions in the Metacognition Research

Research in the past few decades provide us with a clearer picture regarding different aspects of metacognition. For example, we have a better understanding about the cues that influence the creation of TOT and FOK experiences, and the neurocomputational models of confidence provide us with more accurate explanation in regard to different aspects of confidence judgments. However, metacognition research is at its beginning, and there are many unanswered questions in the field that need to be answered. An important question, for example, is whether a general neurocomputational mechanism(s) generates all of the metacognitive judgments or if each metacognitive judgment has its own unique neurocomputational mechanism (e.g., McCurdy et al., 2013; Morales et al., 2018). As the neuroimaging studies have suggested (e.g., Maril et al., 2005; McCurdy et al., 2013), some of the metacognitive judgments may partially share common neural bases, even though differences emerge among the judgments as well.

An interesting approach to investigate this important question is to see if different metacognitive judgments interact with each other and have influence on each other’s predictive outcome. Moreover, to investigate this question further, we need a reliable measure of metacognitive accuracy which will be crucial for the quest to understand the nature of metacognition. For this reason, in the remainder of this chapter, I will focus on these two issues. First, I will briefly discuss the possibility of a general mechanism(s) that may underline all of the metacognitive judgment and the possible interactions between different metacognitive judgments. Then, I will discuss the ways we can evaluate ability of metacognitive judgments to predict the outcome of object-level processes. Finally, I will discuss general recognition theory and the ways we can use it to investigate metacognitive sensitivity of different metacognitive judgments and the interaction between different metacognitive judgments.

General vs. Specific Mechanisms of Metacognition

The dependency of different metacognitive judgment on general or specific neurocomputational mechanism(s) is an important question in the field of metacognition. That is, whether a general neurocomputational mechanism(s) generates all of the metacognitive judgments or if each metacognitive judgment has its own unique set of neurocomputational mechanisms is a critical question which needs to be answered. Whereas some researchers tried to evaluate this important puzzle (e.g., McCurdy et al., 2013; Metcalfe et al., 1993; Morales et al., 2018; Schraw et al., 1995; Schraw & Nietfeld, 1998; Song et al., 2011), the presence of some procedural obstacles hinders the progress toward an answer to this question. For example, a difficulty in this regard arises from the limited cross-talk between research on perceptual metacognition and metamemory research. These two lines of research, even though investigating different aspects of the same construct (i.e., metacognition), seem like two separate islands with their own research agenda and ambitions. The lack of cross-talk between these two seemingly unrelated areas of research is unfortunate, given the existence of evidence for the correlation between perceptual metacognition and metamemory (e.g., McCurdy et al., 2013; Morales et al., 2018).

Regardless of this obstacle, some researchers have tried to investigate this important question at least in some capacities. In general, there are different approaches to investigate commonalities across metacognitive judgments. Although these approaches investigate this question from different points of view, they are all based on a simple assumption: if there is a correlation between a behavioral or neural aspect of a metacognitive judgment (e.g., neural bases or metacognitive sensitivity) and a behavioral or neural aspect of the second metacognitive judgment, then these two metacognitive judgments arise from common neurocomputational mechanism(s). For example, if there is a correlation between the metacognitive sensitivities of FOK and confidence judgments, then, they are likely to be arising from a common neurocomputational mechanism(s). Similarly, if there is a correlation between behavioral or neural aspect(s) of a metacognitive judgment when it is evaluating different object-level tasks, then a common neurocomputational mechanism(s) support this metacognitive judgment when it evaluates different types of object-level information. For example, if confidence shows similar qualities when assessing a visual vs. a memory task, then confidence evaluations of visual and memory arise from a common neurocomputational mechanism(s). Having this assumption in mind, I will review these approaches separately.

The first approach is to compare qualities of a metacognitive judgment when that metacognitive judgment evaluates different tasks within a modality. For example, one may be interested in comparing metacognitive sensitivity of confidence evaluation of visual orientation discrimination and visual motion discrimination. Comparing confidence evaluation of these two tasks, that are visual discrimination, may help us to determine whether confidence judgments of different visual discrimination tasks arise from a common neurocognitive mechanism(s). Using this approach, Schraw et al. (1995) compared metacognitive sensitivity as well as mean confidence ratings between eight different cognitive tasks (history-related questions, geography-related questions, nutrition-related questions, biology-related questions, mathematics-related questions, spatial judgment, general-knowledge questions, and reading comprehension) and found correlations between metacognitive sensitivities as well as the mean confidence ratings across the eight domains (for similar results, see Schraw & Nietfeld, 1998; Veenman et al., 1997). These results indicate that confidence evaluations of different memory processes are based on a common cognitive mechanism(s).

Song et al. (2011) found similar results with regard to confidence evaluation of visual perception. In this study, Song et al. (2011) asked participants to do two perceptual tasks (orientation and contrast discrimination tasks) and to rate their confidence on their performance on each task. Next, they compared metacognitive sensitivity of confidence as well as the mean confidence rating between the two perceptual tasks. The results showed a positive correlation between metacognitive sensitivity of confidence when evaluating orientation discrimination performance and when evaluating contrast discrimination performance. Song et al. (2011) found a similar correlation when comparing the average confidence level across the two perceptual tasks. Taken together, these results suggests that confidence evaluation of visual or memory performance derives from a common cognitive mechanism. This conclusion should not be surprising because confidence judgments (or any other metacognitive judgments) may use a similar set of clues when evaluating accuracy of object-level processes driving from a singular modality such as visual perception. For example, in Song et al's (2011) study, confidence evaluations of different visual perception tasks are based on the quality of evidence in favor of a decision. Hence, the type of stimulus or task should not be of a concern for the neurocomputation(s) that generate confidence judgments. On the other hand, one can question the generalizability of this conclusion to other metacognitive judgments such as FOKs or TOTs, especially because this evidence mostly come from study of confidence judgments.

In line with this criticism, two studies show that different neurocognitive mechanism(s) may underlie FOK for different types of memory information. For example, Reggev et al. (2011) compared the neural bases of semantic and episodic FOKs, and showed fMRI signals in different brain areas associate with each of these two types of FOK judgments. According to Reggev et al. (2011), semantic FOK is associated with the activities in the right IFC, and episodic FOK is associated with the activities in the left MTG, the cuneus, and the posterior cingulate cortex. Moreover, by comparing fMRI correlates of semantic and episodic FOK, Elman et al. (2012) found stronger episodic FOK activations in the left ventral posterior parietal cortex, precuneus, and frontal pole and stronger semantic FOK activations in the right anterior temporal lobe. These results indicate that different neurocognitive mechanisms may support different FOK judgments. These findings suggest that additional research is required to determine whether each metacognitive judgment arises from a common neurocognitive mechanism(s) when evaluating different object-level tasks within a modality.

The second approach to the aforementioned question is to compare qualities of different metacognitive judgments when they are evaluating the same object-level task. This approach was used to evaluate the similarities between the neural bases of confidence and FOK judgments. For example, Pappas et al. (1992) compared the accuracy of FOK and confidence of participants suffering from Alzheimer’s disorder when those participants were performing semantic and episodic memory. According to Pappas et al's (1992) results, confidence judgments were still functional in participants with Alzheimer’s disorder, but they suffered from an impairment of FOK when performing semantic and episodic memory. These results suggest a dissociation between FOK and confidence judgments.

A follow up study by Schnyer et al. (2004) provided additional support for this conclusion. In this study, Schnyer et al. (2004) compared metacognitive accuracy of FOK and confidence judgments in participants with and without lesions to the medial prefrontal cortex (MPFC). Results showed impairment of metacognitive accuracy of FOK judgments in participants who were suffering from a lesion to the MPFC. However, these participants showed intact metacognitive accuracy of confidence judgments, similar to the control participants who did not have any lesions to the MPFC. In line with these results, Pannu et al. (2005) showed impairment of metacognitive sensitivity of confidence judgments when participants with lesions to their frontal lobe were asked to recognize famous faces. These participants, however, showed no signs of impairment of metacognitive sensitivity of FOK judgments. Hence, the results of these three studies indicated that FOK and confidence judgments arise from different neurocomputations within the nervous system. This conclusion is based on the evidence that neurological patients with suffering from Alzheimer's or frontal lesion only exhibit impairment one of these two metacognitive judgments. Therefore, it seems that at least these two metacognitive judgments have different neurocomputational mechanism(s). However, future studies ought to investigate the associations and differences between these two metacognitive judgments more systematically.

TOT and FOK are two different but very similar metacognitive experiences. The extent of the phenomenological similarities between these TOT and FOK raised the possibility that they might share a common neurocomputational mechanism(s). Indeed, some authors have stated that TOTs are specific types of FOK (e.g., Nelson, 2000). For these reasons, some researchers evaluated the behavioral similarities of these two metacognitive judgments. For example, Metcalfe et al. (1993; Experiment 3 & 4) showed that both TOTs and FOKs depend on the familiarity of the cues. Moreover, Schwartz et al. (2000) showed that FOK judgments are correlated with the likelihood of reporting a TOT experience (also see Yaniv & Meyer, 1987).

Schwartz (2008) adopted a different approach to test the similarities of TOT and FOK by examining the impact of working memory load on these two metacognitive experiences. In this study, Schwartz asked participants to answer general knowledge questions. If participants indicated that they did not know the correct answer, they were asked to indicate whether they were experiencing a TOT or they were experiencing a high FOK[15]. To evaluate the impact of working memory load in this study, in half of the trials, Schwartz (2008) presented participants with a series of digits (Experiments 1-3) or a visual shape (Experiment 4) before the general knowledge question and asked participants to memorize those digits or the details of the shape. After responding to the TOT or FOK questions, participants had to recall the provided digits (Experiment 1-3) or recognize the correct object's shape (Experiment 4) in a 2-alternative recognition task. After performing all these tasks, participants were asked to perform a memory recognition tasks in which they had to choose the correct answer to each question from a list of alternatives.

The results showed that the participants were less likely to report experiencing a TOT in the presence of working memory load. Presence of working memory load,

---

[15] This study used a between subject design. Half of the participants were asked to report whether they are experiencing a TOT and the other half were asked to report whether they are experiencing a high FOK.

however, had no impact on the likelihood of reporting an FOK[16]. Additionally, working memory load had no influence on the metacognitive sensitivity of TOTs or FOKs. Hence the results of this and other studies suggests that TOT and FOK may arise from a common neurocomputational mechanism(s), even though additional mechanism(s) is needed for each to happen.

The results of neuroimaging studies also support this conclusion. For example, Maril et al. (2005) asked participants to indicate their level of memory retrieval in a semantic memory task based on the following categories: know, do-not-know, TOT, and feeling of knowing, while recording their fMRI responses in each trail. Comparing fMRI responses in the trials that participants reported TOT and FOK revealed activities in the posterior medial parietal cortex, bilateral lateral parietal cortex, and bilateral superior PFC that was common to both TOT and FOK trials but not to know or do-not-know trials. Moreover, Maril et al. (2005) found TOT specific responses in the ACC, right IFC, right DLPFC and bilateral anterior frontal cortex, which were absent in the trials that participants reported experiencing an FOK. Two compatible conclusion can be drawn from these results. According to the first finding, TOT and FOK are originating from common neurocomputational mechanisms. According to the second finding, even though TOT share similar neurocomputational mechanism(s) with FOK, it also requires additional computations relative to FOK. In contrast, a more recent study did not provide as much evidence for the overlapped neural bases for TOT and FOK (Huijbers et al., 2017).

[16] Note that in the first experiment of this study, the number of FOK reports actually increased in the presence of working memory load and in the last experiment, there was no difference in the number of TOT reports in the presence or absence of working memory load.

According to Huijbers et al. (2017), TOT is associated with stronger activities in the hippocampus, the LPFC, and the retrosplenial cortex than FOK judgment. In summary, behavioral and neural studies of TOT and FOK indicate that a common neurocomputational mechanism(s) may support both metacognitive experiences, but each may also require additional computations which is done through a different mechanisms.

In the third approach to the question of general vs. specific mechanism(s) of metacognition, we compare the qualities of a metacognitive judgment when that metacognitive judgment evaluates object-level processes across different object-level modalities (for example memory vs. visual perception or visual vs. auditory perception). This approach was specially adopted to investigate the neurocognitive bases of confidence judgments when participants provided confidence on the accuracy of their perceptual and memorial performance[17]. For example, McCurdy et al. (2013) asked participants to rate their confidence on their performance in a memory recognition or a visual discrimination task. McCurdy et al. (2013) also acquired each participant's anatomical MRI images and evaluated the correlation between the gray matter volume of participants with their metacognitive efficiencies[18] (meta-d'/d'; see the section titled How to Measure Metacognition) across the two tasks (visual metacognition efficiency vs. metamemory efficiency).

---

[17] It seems impossible to use this approach to investigate qualities of a metacognitive judgment other than confidence because those metacognitive judgments are unique to evaluation of memory processes.

[18] Metacognitive efficiency refers to the ability of a metacognitive judgment to efficiently evaluate object-level information, regardless of qualities of object-level information (see the section titled How to Measure Metacognition)

The behavioral results of this study showed a significant correlation between metacognitive biases as well as a significant correlation between metacognitive efficiencies across the two metacognitive judgments. Additionally, evaluating the correlation between the gray matter volume and metacognitive efficiencies revealed a correlation between the volume of aPFC and visual metacognition efficiency and a correlation between the volume of precuneus and metamemory efficiency. Interestingly, the volume of precuneus was also correlated with visual metacognition efficiency, whereas there was no significant correlation between the volume of aPFC and metamemory efficiency. Further analyses showed that aPFC volume had stronger correlation with visual metacognition efficiency than metamemory efficiency, whereas precuneus volume has similar correlation with visual metacognition and metamemory efficiencies. Finally, McCurdy et al. (2013) found a correlation between the volume of aPFC and precuneus.

These results suggests that confidence evaluation of visual and memory performance derives from distinct mechanism(s) that may interact. This interaction manifested itself as the correlation between visual metacognition and metamemory efficiencies. Other studies supported the first part of this conclusion. That is, other studies found distinct neurocognitive mechanisms for metamemory and visual confidence judgments. For example, Baird et al. (2013) asked participants to provide a confidence evaluation of their performance in a memory retrieval or perceptual discrimination task. Moreover, Baird et al. (2013) acquired each participant’s structural MRI as well as their resting state fMRI signals. In line with McCurdy et al's (2013) results, Baird et al. (2013) showed a significant correlation between visual metacognitive sensitivity and functional connectivity between right lateral aPFC and three clusters including dorsal ACC, the left putamen and a cluster, which was composed of the right putamen, right caudate and thalamus. Additionally, the results showed a significant correlation between metamemory sensitivity and functional connectivity between right medial aPFC and two clusters including central precuneus and intra-parietal sulcus/inferior parietal lobule (for similar results, see Baird et al., 2015). This indicate a distinct neurocognitive mechanism(s) for confidence judgments, when they are evaluating visual vs. memory information.

In addition, Fleming et al. (2014) showed selective impairment of visual metacognition efficiency in participants with a lesion to their aPFC. However, these participants showed intact metamemory efficiency. These results are compatible with the earlier finding that aPFC selectively processes confidence evaluation of visual information. More recently, Morales et al. (2018) found greater BOLD signals from middle cingulate gyrus, insula, precuneus, hippocampus and cerebellum for the trials that participants reported metamemory confidence than the trials that they reported visual metacognition confidence. The opposite contrast did not show a significant BOLD signal difference. Moreover, BOLD signal from parietal cortex was associated with high level of metamemory confidence but not with high level of visual confidence. High level of visual confidence, however, was not associated with a BOLD signal. Morales et al. (2018) also used multivariate pattern analysis of fMRI (MVPA) to further test the distinct mechanisms of visual vs. metamemory confidence. These results showed that the ACC and aPFC can distinguish metamemory confidence from visual confidence. Moreover, these results showed that right aPFC and precuneus are more sensitive in decoding memory confidence and left aPFC and ACC are more sensitive in decoding visual confidence.

In summary, the results of neuroimaging as well as neuropsychological studies of visual and metamemory confidence indicate the existence of distinct neurocognitive mechanisms supporting metamemory and visual confidence judgments. However, the behavioral results are mixed. Although some studies found evidence for correlation between behavioral aspects of visual and metamemory confidence (metacognitive accuracy and efficiency as well as mean confidence rating; McCurdy et al., 2013; Morales et al., 2018; also see Faivre et al., 2018), other studies failed to show such correlation (e.g., Baird et al., 2013, 2015).

Lee et al. (2018) argued that a number of statistical and methodological differences are responsible for the behavioral differences between the studies that found such correlation and studies that did not. Among these differences is the difference confidence and object-level tasks used in these seems to be very consequential. For example, McCurdy et al. (2013) used similar 2-alternative forced-choice (2AFC) task for both object level memory and visual tasks, whereas Baird et al. (2013) used 2AFC task as a visual task and yes/no task as a measure of memory performance. According to Lee et al. (2018) this difference may be responsible for the inconsistent behavioral results. To remedy this, Lee et al. (2018) evaluated the correlation between metamemory and visual confidence across three experiments using three different conditions: 2AFC tasks as the measure of memory and visual tasks (Experiment 1), 2AFC as the measure of visual and yes/no detection as the measure of memory (Experiment 2), and yes/no detection task as the measure of memory and visual task (Experiment 3). Experiment 1 showed a similar results as McCurdy et al's (2013)study. That is, there was a correlation between metacognitive efficiency of metamemory and visual confidence judgments. Experiment 2, on the other hand, replicated

Baird et al's (2013) results. That is, there was no correlation between metacognitive efficiency of metamemory and visual confidence judgments. Finally, there was no significant correlation between metacognitive efficiency of metamemory and visual confidence judgments in Experiment 3. That is, the use of yes/no detection task as an object-level task might be responsible for lack of correlation between metacognitive efficiency of metamemory and visual confidence judgments (for similar results, see Samaha & Postle, 2017). Lee et al. (2018) postulated that suboptimality of confidence evaluation of yes/no detection task after a no response might be a reason for the lack of correlation between the two metacognitive efficiencies. Future research needs to evaluate this and other possibilities in regard to the impact of type of object-level task on the correlation between metacognitive efficiency of metamemory and visual confidence judgments.

In conclusion, there are sufficient evidence for distinct neurocognitive mechanisms supporting visual and metamemory confidence. Moreover, the studies point to the possibility of a general mechanism of confidence generation (which may originate in the precuneus). That is, confidence evaluation of visual and memory information may arise from a general mechanism(s), even though both types of confidence relay on additional computations specific to themselves. Finally, the behavioral correlation between metamemory and visual confidence judgments support the existence of both general and specialized mechanisms for metamemory and visual confidence judgments. Moreover, the behavioral results also support the notion that the specialized mechanisms of visual and metamemory confidence judgments may interact.

This brings us to the final conclusion of this section. Converging evidence from studies utilizing three approaches to the question of common vs. specialized mechanism(s) of metacognition support the notion of distinct neurocognitive mechanisms supporting different metacognitive judgments, as well as a common metacognitive judgment that may be involved in initial generation of at least some of the metacognitive judgments (e.g., TOT and FOK, or visual and metamemory confidence). Moreover, research indicate that neurocognitive mechanism(s) of different metacognitive judgments may interact, which manifest itself as a behavioral correlation between different metacognitive judgments. However, this line of research is inconclusive. First, we do not have a sufficient understanding regarding the neurocognitive mechanisms of every metacognitive judgments. Second, the evidence for the existence of a common neurocognitive mechanism that support or initiate all of the metacognitive judgments is limited to the comparison of only few metacognitive judgments (for example TOT and FOK as well as visual and metamemory confidence). Therefore, future research needs to investigate this issue more systematically.

One way to do this, in my opinion, is to investigate possible interaction between different metacognitive judgments. I argue that a new model-based analysis that our team recently introduced may pave the way for this purpose. For this reason, in a part of this study I employed this new model-based analysis extracted from general recognition theory to investigate the possible impact of experience of TOT and FOK on metacognitive sensitivity of TOT. I will introduce this model-based analysis in a later section, but first I will need to provide an overview of the measures of metacognitive sensitivity, which will be the topic of the next section.

How to Measure Metacognition

Many studies from different laboratories have indicated that the metacognitive evaluations of object-level processes are usually, but not always, accurate. That is, in most situations metacognitive judgments provide us with an accurate assessment of object-level processes. This means that we can consider metacognitive judgments as accurate predictors of object-level processes. For example, different studies have shown that TOT can predict the successful retrieval of the missing information in future attempts (e.g., R. Brown & McNeill, 1966; Schwartz, 2010) and confidence judgments are indicators of accuracy of perceptual and memory decisions (e.g., Chua et al., 2012; Maniscalco et al., 2020; Perfect, 2002).

The precision of metacognitive judgments in predicting accuracy of cognitive and perceptual processes is called metacognitive sensitivity, metacognitive accuracy, or resolution[19]. In general, metacognitive sensitivity refers to the ability of metacognitive system to accurately predict the outcome of a cognitive or perceptual process. For example, if I am highly confident that I can recall the name of the highest mountain peak in Iran (Mt. Damavand) and if I can do so, then I am showing signs of high metacognitive sensitivity. If, one the other hand, I am highly confident that I can recall the name of the highest mountain peak in Iran but then I fail to do so, then I am showing signs of low metacognitive sensitivity.

To understand metacognitive sensitivity better, we need to distinguish it from object-level sensitivity and metacognitive criterion (or metacognitive bias). Object-level

---

[19] I will use these three terms interchangeably.

sensitivity or type-1 sensitivity is the ability of participants to separate two categories of stimulus classes (for example old from new images). We define sensitivity within the framework of signal detection theory (SDT; see Green & Swets, 1966; Macmillan & Creelman, 2005). To introduce signal detection theory, we can start with an example from a hypothetical perceptual experiment. In this experiment, we present participants with a visual target stimulus with a near threshold intensity. In half the trials we do not present any stimulus and we call these trials "catch trials". Participants' task in each trial is to report if they saw the stimulus. According to SDT, the intensity of the internal representation of the stimulus varies from one trial to the next. A univariate probability distribution represents the intensity of the internal representation of the target stimulus across trials (signal distribution. See Fig. 2a). In addition, SDT assumes the presence of a noise in the absence of the target stimulus (catch trials) [20] and assumes that the intensity of the internal representation of the noise also varies from one trial to the next. Therefore, SDT represents the intensity of the internal representation of the target stimulus across trials using another probability distribution (noise distribution). According to SDT, noise distribution that has a lower mean than the signal distribution.

Moreover, SDT assumes that participants use a decision bound, which we call criterion or bias, to make a decision in such experiment. If the intensity of the internal representation exceeds the criterion in a trial, participant will report seeing the target (even in the absence of the target). Otherwise, participants report not seeing the target, even if we

[20] It is important to note that the noise is present in the presence and absence of signal. For this reason, SDT calls the distribution of the signal the signal plus noise distribution.

presented the target in this trial. In this and any other experiments, participants may adopt a different criterion to make decision about the presence and absence of the target. For example, a participant may shift their criterion toward the signal distribution and therefore adopt a conservative criterion. Another participant may shift their criterion toward the noise distribution and adopt a liberal criterion. It is important to note that we label liberal and conservative criterion in reference to the optimal criterion that is a point in the SDT model, at which the noise and signal distribution intersect. Based on this, distance of a participants' adopted criterion from the optimal criterion quantifies the magnitude of this participant's decision bias[21].

SDT defines sensitivity (d') as the standardized distance between signal and noise distribution, and it represents ability of participants to discriminate signal from noise. Hence, as the distance between two distribution increases, so does the strength of sensitivity. Based on this, a high sensitivity means that participants can completely distinguish signal from noise and a low sensitivity or zero sensitivity means that participants cannot tell the difference between signal and noise. Note that sensitivity is mathematically independent of decision bias, meaning participants decision bias has no influence on their sensitivity. For example, a participant may adopt a conservative criterion or a liberal criterion to classify the stimuli into signal and noise. This, however, has no influence on their sensitivity. For this reason, we assert that sensitivity is bias-free. I will discuss the differences between sensitivity and metacognitive sensitivity later in this

[21] Note that the level of bias is usually stable within a participant and shift in a bias in a participant may happen very slowly. However, decision bias has a variance across participants.

chapter, as these differences are important for better understanding of metacognitive sensitivity.

In addition to type 1 sensitivity, we should also distinguish metacognitive sensitivity from metacognitive bias or metacognitive criterion. Metacognitive bias refers to participants' tendency to use a certain level of a metacognitive judgment. For example, a participant may adopt a conservative criterion and report a low confidence level on their judgments even if there is enough evidence to support their judgment. On the other hand, a participant may adopt a liberal criterion and report a high confidence level on their judgments even if there is enough evidence against the judgment. It is important to note that metacognitive bias is indispensable element of any metacognitive judgment, and it is crucial to quantify the level of it influence on different metacognitive judgments in different conditions, especially if we are interested in estimating metacognitive sensitivity.

In the rest of this section, I will review some of the measures that are used to estimate metacognitive sensitivity, and I will discuss their weaknesses and strengths in evaluating metacognitive sensitivity. After that, I will present the model-based analysis based on general recognition theory that our team proposed recently for studying conscious and nonconscious perception (Pournaghdali et al., in revision) and will discuss how we can use this model-based analysis to study metacognitive sensitivity.

But before moving forward, we should establish a few criteria for evaluating these measures. First, when assessing metacognitive sensitivity, one should take into account metacognitive bias or metacognitive criterion, which is an inseparable component of metacognitive judgments. For example, in a FOK task a participant may adopt a liberal metacognitive bias and report a high level of FOK. Another participant, however, may adopt a conservative metacognitive bias and report a low level of FOK. As I mentioned before the actual ability of a participant's metacognitive judgment to accurately predict their performance in an object-level task is separable from their tendency to report a specific level of a metacognitive judgments. Hence, a measure of metacognitive sensitivity should be able to reflect the separability of metacognitive sensitivity from metacognitive bias.

A measure of metacognitive sensitivity that can separate metacognitive sensitivity from metacognitive bias is important for understanding different aspects of metacognition. First, to understand the mechanism(s) by which metacognitive system makes judgments about object-level processes (and the efficacy of such mechanism(s) in tracing the accuracy of object-level processes (e.g., Kellij et al., 2021; Koriat, 1993; Maniscalco et al., 2016, 2021), we need a measure of metacognitive sensitivity that can dissociate metacognitive sensitivity from metacognitive bias. Moreover, one might be interested in studying poor metacognitive sensitivity or chance-level metacognitive sensitivity and the factors that may cause such metacognitive inefficiency (e.g., Shekhar & Rahnev, 2021a, 2021b). Without a proper measure of metacognitive sensitivity, evaluating metacognitive inefficiency because cumbersome, if not impossible. In addition, enhancing metacognitive sensitivity is a topic of interest in many areas including education (e.g., Ariel et al., 2009; Miller & Geraci, 2014; Schwartz & Efklides, 2012) and criminal justice (e.g., Gawrylowicz et al., 2014; Perfect, 2002). Moreover, to evaluate the effectiveness of different methods of metacognitive enhancement, one needs an accurate measure of metacognitive sensitivity to evaluate metacognitive sensitivity for before and for after applying the enhancement method. Finally, impairment of metacognitive processes needs to be evaluated in some psychological and neurological conditions such as Alzheimer's (e.g., Cosentino et al., 2007; Garcia-Cordero et al., 2021; for review, see Hallam et al., 2020) Schizophrenia (e.g., Bacon et al., 2018; Lysaker et al., 2011; for review, see Rouy et al., 2021) and depression (e.g., Capobianco et al., 2020; Papageorgiou & Wells, 2003). An interesting question in regard to such conditions, is whether observed metacognitive impairment is the results of impairment of metacognitive sensitivity or impairment of metacognitive criterion setting (i.e., substantial elevation or demotion of metacognitive criterion). Therefore, to investigate this question, one must be able to accurately dissociate the impairment of metacognitive bias from the impairment of metacognitive sensitivity. Based on these reasons, a measure of metacognitive sensitivity should be bias-free.

Second, a measure of metacognitive sensitivity should be able to dissociate the possible effect of object-level processes from the estimated metacognitive sensitivity. That is, an optimal measure of metacognitive sensitivity should be able to distinguish metacognitive sensitivity from type 1 sensitivity and type 1 bias. Especially dissociating metacognitive sensitivity from object-level sensitivity is critical for our understanding of metacognitive sensitivity, because in many cases, the qualities of object-level processes have direct influence on the metacognitive sensitivity of different metacognitive judgments. For example, in an easy perceptual task, participants may have high metacognitive sensitivity only because object-level processes provide metacognitive system with a clear information with a high signal to noise ratio. On the other hand, in a situation when object-level processes are not optimal, the metacognitive system may not receive sufficient information to evaluate object-level processes, and therefore metacognitive sensitivity may drop substantially. In these two cases, high and low metacognitive sensitivities are the results of optimal and dysfunctional object-level processes respectively and not the results of optimal and dysfunctional metacognitive sensitivity. Therefore, it is important for a measure of metacognitive sensitivity to separate the object-level and meta-level processes.

Now, by having these two criteria in mind, I will review some of the most popular measures of metacognitive sensitivity[22]. To begin our review of the measures of metacognitive sensitivity, I start by a hypothetical memory experiment. In this study, early learners of the Spanish language are presented with Spanish words for fruits and animals. The participants' task is to indicate if the target word belongs to the fruit or the animal category (memory recognition task[23]) and to rate their confidence on their response to the memory task. In this hypothetical study, we want to know whether metacognitive confidence judgments can provide an accurate assessment of participants' performance in the memory task. That is, we want to evaluate metacognitive sensitivity of confidence within this hypothetical experiment.

To evaluate metacognitive sensitivity in this hypothetical experiment, first we should categorize participants' confidence responses based on the accuracy of responses in the memory recognition task (see Table 1). We refer to the metacognitive responses as type 2 responses or judgments, which are in contrast to type 1 judgments that are object-level judgments, in this case concerning the judgment of a word as animal or fruit. Table 1

---

[22] A comprehensive review of these measures is beyond the scope of this study (for comprehensive review of these measures, see Barrett et al., 2013; Fleming & Lau, 2014).

[23] Note that this is an object-level judgment

summarizes the categorization of type 2 responses based on type 1 accuracy. In this table, the four response cells represent four categories of type 2 responses: hit, false alarm, miss and correct rejection. A type 2 hit happens when a participant responds correctly to the memory recognition task and also reports high confidence (H2). A type 2 false alarm happens when a participant responds incorrectly to the memory recognition task but reports high confidence (FA2). A type 2 miss happens when a participant responds correctly to the memory recognition task but reports low confidence (M2). Finally, a type 2 correct rejection happens when a participant responds incorrectly to the memory recognition task and also reports low confidence (CR2).

Table 1 Classification of type 2 (metacognitive) responses based on type 1 accuracy.

	Correct Recollection	**Incorrect Recollection**
High Confidence	Hit	False Alarm
Low Confidence	Miss	Correct Rejection

Based on this, we can define hit rate (HR2) and false alarm rate (FAR2) as follow:

$$\text{HR2} = \frac{\text{hit}}{\text{hit} + \text{miss}} \qquad (1)$$

$$\text{FAR2} = \frac{\text{false alarm}}{\text{false alarm} + \text{correct rejection}} \qquad (2)$$

A popular approach to evaluate the metacognitive sensitivity, especially in the metamemory research, is to correlate performance in the object-level task (for example memory recall task) and metacognitive judgment regarding this task (for example confidence rating). To this end, we can use the Goodman–Kruskall gamma correlation (gamma correlation for short; see Nelson, 1984). The gamma correlation is a ranked correlation between object-level performance and metacognitive judgment. We estimate the gamma coefficient, by plugging HR2 and FAR2 estimates, resulted from equations 1 and 2, into the following equation:

$$G=\frac{\text{HR2-FAR2}}{\text{HR2+FAR2 (2*HR2(FAR2))}} \qquad (3)$$

After estimating the gamma coefficient, we contrast it against the chance-level (zero; for example, see Hanczakowski et al., 2017; Schwartz, 2010; Schwartz & Metcalfe, 1992). Higher-than-chance positive gamma correlation is an indication of metacognitive sensitivity. That is, a positive gamma correlation shows that a metacognitive judgment can accurately predict the object-level performance. Chance-level gamma correlation means that metacognitive system cannot discriminate correct from incorrect object-level performance. Lower-than-chance negative gamma correlation, which seems counterintuitive for metacognitive sensitivity, means that a metacognitive judgment mis-predicts object-level performance: for example, higher confidence for incorrect object-level responses and lower confidence for correct object-level responses. Such instances are rare but have been observed (Benjamin et al., 1998).

Although gamma correlation has been a popular measure of metacognitive accuracy, it does not meet the two criteria for a reliable measure of metacognitive sensitivity. First, an estimated gamma coefficient is influenced by participant's metacognitive bias (Fleming & Lau, 2014). That is, having a liberal or a conservative metacognitive bias may influence the estimation of gamma coefficient (also see Masson & Rotello, 2009). Hence, gamma correlation is not bias-free. Second, by using the gamma coefficient as a measure of metacognitive sensitivity we are not able to evaluate the influences of type-1 sensitivity and type-1 bias on the estimation of metacognitive sensitivity (Fleming & Lau, 2014). For example, a significant high gamma coefficient may be the results of an easy object-level task or an efficient metacognitive evaluation of the object-level processes. A chance-level gamma coefficient, on the other hand, might be the results of two possibilities: either metacognitive system is not working optimally or object-level processes are not providing sufficient information for the metacognitive system. In conclusion, gamma correlation is unable to meet the two requirements for an optimal measure of metacognitive sensitivity. Therefore, I advise against using this measure for evaluating metacognitive sensitivity, especially when sensitivity measures are crucial to the theoretical questions being asked.

An alternative to gamma correlation for evaluating metacognitive sensitivity is to use type 2 sensitivity (a′) derived from type 2 SDT (Kunimoto et al., 2001; also see Benjamin & Diaz, 2008). According to type 2 SDT, correct and incorrect object-level responses are probabilistic, and we can represent each response type (correct vs. incorrect) using a univariate probability distribution. A univariate probability distribution represents the probability of correct responses across trials (correct distribution) and a univariate probability distribution with a lower mean than the correct distribution represents the probability of incorrect responses across trials (incorrect distribution). Type 2 SDT assumes participants use a metacognitive criterion to make metacognitive decisions in such experiments. If a portion of a probably distribution exceeds the type 2 criterion, participants report high confidence for that decision (even if the decision is incorrect), and if a portion of a probability distribution does not reach the type 2 criterion, participant report low confidence for that decision (even if the decision is correct). Similar to type 1 bias, participants may shift their criterion toward the incorrect distribution (liberal type-2 criterion) and report a high confidence level even when there is enough evidence against their type-1 decisions. Participants may also adopt a conservative criterion and shift their type-2 criterion toward the correct distribution. In this case, participants will report a low confidence level in majority of trials even if there is enough evidence supporting their type-1 decision.

However, type 2 SDT proposes a bias-free measure of metacognitive sensitivity, which is called type 2 sensitivity (a'). type 2 sensitivity, which is the standardized distance between the mean of correct and the mean of incorrect distributions, represents participants' ability to separate correct from incorrect decisions using their metacognitive judgments. We can estimate type 2 sensitivity using the following equation:

$$a' = z(HR2) - z(FAR2) \quad (4)$$

Where z is the z-score or the cumulative normal distribution function. Accordingly, a high a' means that participants can completely distinguish correct from incorrect decisions and a low sensitivity or zero sensitivity means that participants cannot tell the difference between correct and incorrect responses because the two distributions completely or almost completely overlap. Moreover, this approach assumes that the value of type 2 criterion has no influence on type 1 sensitivity, and therefore a' is a bias-free measure of metacognitive sensitivity.

Whereas type 2 sensitivity was introduced based on the assumption that it can separate metacognitive sensitivity from metacognitive bias, later research has shown that changes in bias, systematically influences the estimated type 2 sensitivity (Evans & Azzopardi, 2007). That is, type 2 sensitivity is not bias-free (also see Galvin et al., 2003). This seems counterintuitive, as SDT can completely separate sensitivity from bias at the type 1 level distribution. The reason for bias-dependency of type 2 sensitivity is as follow. Type 1 SDT assumes that the signal and noise distributions are gaussian (in most cases) and have equal variances[24] (Green & Swets, 1966; Macmillan & Creelman, 2005). Type 2 sensitivity approach to metacognitive sensitivity assumes that not only type 1 distributions are gaussian with equal variances but type 2 distributions (correct and incorrect distributions) are also gaussian with equal variances (see Kunimoto et al., 2001). Even if this assumption holds for type 1 distributions, it has been shown that type 2 distributions are non-gaussian and have unequal variances (Galvin et al., 2003). The violation of this assumption when estimating type 2 sensitivity causes inaccurate estimation of metacognitive sensitivity that is bias-dependent. Moreover, when using type 2 sensitivity, we are unable to distinguish the influence of type 1 sensitivity and bias on the estimated metacognitive sensitivity (Fleming & Lau, 2014). Hence, type 2 sensitivity is unable to dissociate the influences of type 1 and type 2 processes on the estimation of type 2 sensitivity. For these reasons, type 2 sensitivity is not an optimal measure of metacognitive sensitivity.

---

[24] Note that type 1 SDT does not necessarily assumes gaussian signal and noise distribution with equal variances. These assumptions can and should be tested by assessing the shape of the empirical receiver operating characteristic curve (see Selker et al., 2019).

Potentially, we can resolve the problems of type 2 sensitivity using type 2 receiver operating characteristic (type 2 ROC) curve, especially because type 2 ROC curve does not have the same underlying assumptions about the shape and variance of correct and incorrect distributions as type 2 sensitivity (Fleming & Lau, 2014). Type 2 ROC curve is a plot that contrast type 2 hit rate and type 2 false alarm rate against each other at different criteria (see Galvin et al., 2003; Masson & Rotello, 2009). To construct a type 2 ROC curve, one can ask participants to do a confidence judgment task with more than two levels (for example four levels: "not at all confident", "a little confident", "somewhat confident", and "very confident"). Here, each level of confidence judgment can be a unique criterion with a unique pair of type 2 hit and type 2 false alarm rates. In this case, "not at all confident" is the lowest level of criterion (liberal criterion). Any confidence judgment above "not at all confident" plus a correct recognition response is a type 2 hit and any confidence judgment above "not at all confident" plus an incorrect recognition response is a type 2 false alarm. After estimating the pair of type 2 hit and type 2 false alarm rate for this confidence level, we do the same for the remaining levels of criterion (a little confident", "somewhat confident", and "very confident") and estimate a pair of type 2 hit and type 2 false alarm rates for each of them. Plotting pairs of type 2 hit and type 2 false alarm rate will result in type 2 ROC curve.

After estimating the type 2 ROC curve, we can use the estimated area under the curve as a measure of metacognitive sensitivity, which is independent of metacognitive bias. However, at least two studies have shown that parameters of type 1 SDT regarding object-level tasks (type-1 sensitivity and type-1 bias) may influence the estimation of type 2 ROC curve (Galvin et al., 2003; Higham et al., 2009). Moreover, a recent study reported that the magnitude of type 2 bias (metacognitive bias) may indeed influence the estimated area under the curve of a type 2 ROC curve (Shekhar & Rahnev, 2021a). Therefore, the type 2 ROC curve is also not bias-free.

More recently, Maniscalco and Lau (2012, 2014) proposed meta-d' as a measure of metacognitive sensitivity. According to Maniscalco and Lau (2012), the value of type 1 sensitivity and type 1 bias determine the shape of the type 2 ROC curve (also see Galvin et al., 2003). Based on this, knowing the empirical type 2 ROC curve, we can determine the type 1 sensitivity that an optimal type 2 observer (metacognitive observer) has in order to show the empirical type 2 ROC results. Based on this, meta-d' is a d' that we expect to see given the type 2 ROC curve of metacognitive optimal observer (for the mathematics of meta-d', see Maniscalco & Lau, 2012, 2014). Meta-d' seems to capture metacognitive sensitivity more accurately than other measures. Furthermore, because meta-d' has the same scale as type-1 d', we can compare them to learn more about metacognitive sensitivity. This can be done by dividing meta-d' by type 1 d' or by subtracting meta-d' from d'. By doing so, we eliminate the influence of type 1 sensitivity on the metacognitive sensitivity, which is estimated by meta-d'. M-ratio is the results of dividing or subtracting meta-d' by or from d', and it is an index for metacognitive efficiency (Maniscalco & Lau, 2012, 2014; also see Fleming & Lau, 2014). That is, M-ratio quantifies the ability of a metacognitive judgment to efficiently evaluate object-level information, regardless of qualities of object-level information.

Comparing meta-d' and type 1 d' and therefore estimation of M-ratio is crucial for studying different aspects of metacognition. For example, we can use this measures to evaluate the neural bases of metacognitive sensitivity of different metacognitive judgments, by dissociating metacognitive sensitivity from type 1 sensitivity (e.g., Morales et al., 2018). Moreover, the aforementioned comparison is especially useful when we want to study the sources of metacognitive inefficiency (for a review of metacognitive inefficiency, see Shekhar & Rahnev, 2021b) or when metacognitive processes are impaired as the results of neurological incidents (e.g., Ko & Lau, 2012). Hence, introduction of meta-d' and M-ratio opens the opportunity for scientific progress in different areas of metacognition research.

However, recently Shekhar and Rahnev (2021) reported that the value of meta-d' may be influenced by metacognitive bias, in a way that increasing the level of metacognitive bias (i.e., bias becomes more conservative) systematically reduces the value of meta-d'. The reason for this effect is not clear, and more research is needed to examine how metacognitive bias may influence the value of meta-d'. In summary, although there are many measures of metacognitive sensitivity, meta-d' seems to provides a more precise estimation of metacognitive sensitivity, and it is recommended to be used. However, the search for a measure of metacognitive sensitivity is not over, and I argue that we should seek measures that are bias-free and be able to potentially separate object-level effects from metacognitive sensitivity. Moreover, as I mentioned in the previous section, the study of interaction between different metacognitive judgments is critical for the scientific understanding of metacognition. The current measures of metacognitive sensitivity, however, are unable to help us in this line of research. Therefore, a new measure of metacognitive sensitivity is needed to allow us to evaluate the interaction between different metacognitive judgments. To this end, I argue we can use a multidimensional extension of signal detection theory to estimate metacognitive sensitivity and to evaluate the interaction between different metacognitive judgments. In the next section, I will introduce this idea.

General Recognition Theory and Metacognition

As mentioned, my goal in this dissertation is to introduce a new approach of evaluating metacognitive sensitivity that is based on a multidimensional extension of SDT called general recognition theory (GRT; Ashby & Soto, 2015; Soto et al., 2017). For this reason, I first briefly review GRT. GRT is a multidimensional extension of SDT for conditions in which there are multiple cognitive dimensions. These dimensions can be perceptual (facial expression and facial identity dimensions) or can be cognitive (metacognition and memory recognition dimensions).

To describe GRT and how one uses it to evaluate interaction between different dimensions, I start with an example of its application. In a hypothetical study, early learners of Spanish and Portuguese are presented with both Spanish and Portuguese words for fruits and animals. In each trial, we present a word from our list, and each participant has to indicate if the target word is a fruit or an animal and also to indicate if it is a Spanish or Portuguese word. In this hypothetical experiment, therefore, there are four categories that each participant needs to discriminate: "Fruit-Spanish," "Fruit-Portuguese," "Animal-Spanish," and "Animal-Portuguese."

According to GRT, the internal representation of each word category varies from one trial to the next along two dimensions of "language" and "fruit-animal" (see Fig 3a). For example, the internal representation of words belong to "Fruit-Spanish" category varies from one trial to the next along the two dimensions of "language" and "fruit-animal." A bidimensional probability distribution represents the variation in the internal representation of each category along both dimensions at the same time. In our example, a bidimensional probability distribution (the yellow circle in Fig 3a) represents the variations in the internal representation of “Fruit-Spanish.” By examining the shape and relative position of each distribution to other distribution, GRT provides us with assessment of different types of interactions between multiple dimensions (Ashby & Soto, 2015; Soto et al., 2017).

I argue that, in general, GRT is the best available tool for investigating the interaction between different cognitive and perceptual dimensions (Ashby & Soto, 2015), such as the interaction between metacognitive experiences and different cognitive and perceptual processes. Our team recently used GRT to study the interaction between visual consciousness (or awareness) and perceptual processing (Pournaghdali et al., in revision). In this study, we used continuous flash suppression (CFS; Tsuchiya & Koch, 2005) to suppress emotional faces (fearful vs. neutral). At the end of each trial, we asked participants to perform a conscious detection task with two alternatives (yes/no), and a perceptual discrimination tasks with two alternatives (fearful/neutral). After fitting a GRT model to the data, we used the estimated parameters of the fitted GRT model to construct a sensitivity vs awareness curve (or SvA curve for short), which represents sensitivity in the perceptual discrimination for every value of awareness. In this study, we showed that participants can recognize facial expression of faces in the absence of awareness Regardless of the results of this study, I argue that this GRT-based analysis provides us with a unique opportunity to study the interaction between metacognitive judgments and different cognitive and perceptual processes.

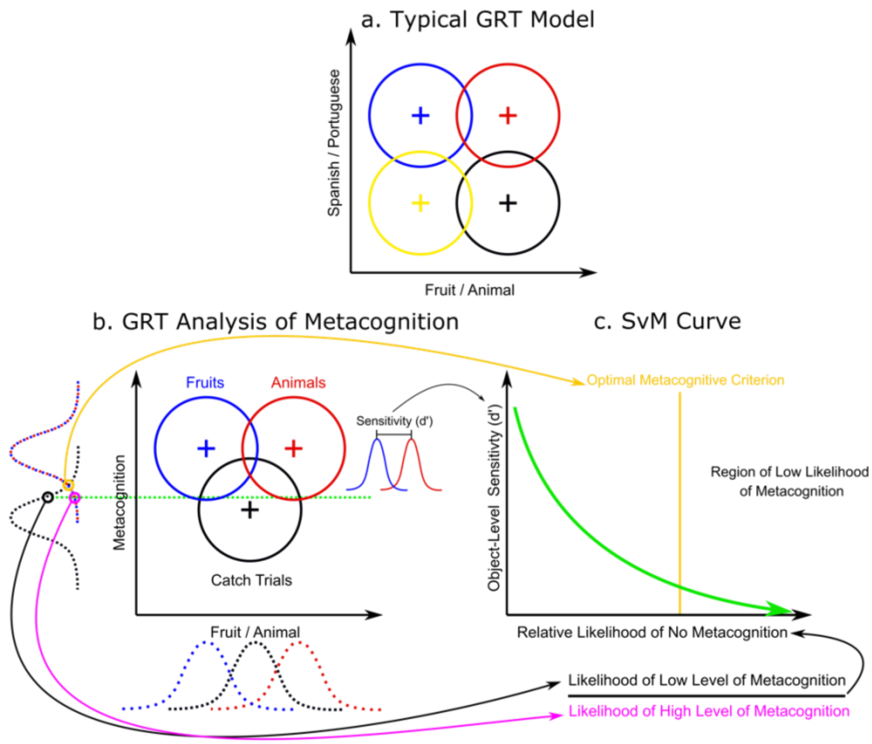

Fig. 3 GRT Analysis of Metacognitive Sensitivity. (a). A typical GRT model. In a hypothetical experiment, participants are presented with Spanish and Portuguese words for fruits and animals. In each trial, we present a word from the list, and each participant has to indicate if the target word is a fruit or an animal and also indicate if it is a Spanish or Portuguese word. GRT represents the variations in the internal representation of each category in a bidimensional space, with the x-axis represents variations along the dimension of fruit-animal and the y-axis represents variations along the dimension of language. Each circle in the bidimensional space represents variations of a unique category (for example Spanish-Fruit) in both dimensions simultaneously. In this graph, the yellow circle represents variations in the internal representations of "Spanish-Fruit" category, the black circle represents variations in the internal representations of "Spanish-Animal" category, the blue circle represents variations in the internal representations of "Portuguese-Fruit" category, and finally the red circle represents variations in the internal representations of "Portuguese-Animal" category. (b). GRT analysis of metacognitive sensitivity. In a hypothetical study, participants are presented by Spanish words for fruits and animals as well as made-up Spanish-like words with no meaning (catch stimuli, e.g., abajero). Participants' task is to classify each word as a fruit or an animal, and to rate their confidence on their classification response with two alternatives: high and low confidence. The x-axis represents the variation in the internal representation of each stimulus along the object-level dimension (fruit-animal), and the y-axis represents the variation in the internal representation of each stimulus along the metacognitive dimension. GRT represents the variation in the internal representation of each stimulus condition (fruits, animals, and catch trials) along both dimensions by a bidimensional probability distribution depicted by a circle in this graph. The blue circle represents variations in the internal representations of "Fruit" category, the red circle represents variations in the internal representations of "Animal" category and the black circle represents variations in the internal representations of "catch trials." (c). SVM curve extracted from the GRT model. The x-axis of an SvM curve is the relative likelihood of no metacognition, with zero representing the strongest level of a metacognitive experience. The y-axis of an SvM curve is object-level sensitivity, with zero representing the chance-level. The objective criterion (yellow vertical line) divides the x-axis of an SvM curve into two areas: the area of high likelihood of metacognition, which is to the left of objective criterion, and the area of low likelihood of metacognition, which is in the right of objective criterion. The green curve is the SvM results extracted from the GRT model.

In the current study, my aim is to expand GRT-based analysis to investigate metacognitive sensitivity of metacognitive judgments. That is, I am intend to use a GRT model to investigate the interaction between metacognitive experiences and different object-level tasks (cognitive or perceptual). Therefore, in my analysis, the first dimension of interest is metacognition, and the second dimension of interest is an object-level cognitive or perceptual task. To implement GRT for evaluating metacognitive sensitivity, participants have to provide a type-1 (i.e., object-level) judgment about the stimulus and type-2 (i.e., metacognitive) judgments about their type-1 performance. For example, in a hypothetical study, beginning learners of Spanish are presented by Spanish words for fruits and animals. We also present participants with a third category of stimuli, which are made-up Spanish-like words with no meaning, necessary as catch trials (e.g., abajero, which has no meaning in Spanish). Participants' task in this hypothetical study is to indicate their feeling that their answer was correct for each word as a fruit or an animal (a confidence task with two levels: high vs. low) and to classify each word as a fruit or an animal (object-level classification task).

Figure 3b illustrates the GRT model fitted to the data from the hypothetical experiment described above. In this model, the x-axis represents the variation in the internal representation of each stimulus along the object-level dimension (fruit-animal), and the y-axis represents the variation in the internal representation of each stimulus along the metacognitive dimension. The variation in the internal representation of each stimulus condition (fruits, animals, and catch trials) along both dimensions is represented by a bidimensional probability distribution (depicted by an ellipse) in the two-dimensional space. In the model, we represent the catch trials with a bidimensional distribution, which is centered at zero in both dimensions. The "fruits" and "animals" categories are represented by bidimensional distribution that are higher in metacognition dimension. Along the object-level dimension, the bidimensional distributions representing the "fruits" and "animals" categories are away from zero in this dimension but in different direction (for example, the "fruit" distribution is away from zero towards negative values and the "animal" distribution is away from zero toward positive values in this dimension[25]).

After fitting the GRT model to the behavioral data, we can estimate two parameters for every value of metacognition along the metacognition dimension (the green dotted horizontal line in Fig. 3b). The first parameter is the relative likelihood of no metacognition, which is the results of dividing the low likelihood of metacognition by the high likelihood of metacognition[26] (also see Fig 3c). The second parameter is the sensitivity in the object-level task, which is the standardized distance between the mean of two stimulus (e.g., fruit and animal) distributions. To reiterate, for every point along the metacognitive dimension, we estimate the relative likelihood of no metacognition and sensitivity in the object level tasks.

---

[25] Note that negative and positive values in this case are relative and are not absolute. That is, negative value (away from zero toward the left side of the dimension) are not negative in reality. They are just values that are different from zero in the left side of zero.

[26] This model considers any metacognitive judgment as a continuous variable, even if we use a binary task to report it. For example, experience of TOT, according to this model, is continuous. Hence, different magnitudes of TOT experiences between no TOT and full-strength TOT are possible. That is, participants may experience different levels of TOT such as very weak TOT, moderate TOT and very strong TOT. In this example, a participant may experience a very weak TOT, which may not be easily distinguishable from not experiencing a TOT or may experience a very strong TOT (also see Schwartz et al., 2000).

After estimating these two parameters, we estimate an objective criterion based on an optimal observer. In theory, the objective criterion is an internal cutoff point that an optimal type-2 (metacognitive) observer uses to indicate if they have a high or low metacognitive experience. That is, an optimal observer uses this criterion to separate trials that they should have a high level of metacognition for (i.e., those that are not catch trials) from those trials that they should not have a high level of metacognition for (i.e., catch trials). In this model-based analysis, the objective criterion is the point in the y-axis of the GRT model, where the likelihood of high level of metacognition equals the likelihood of low level of metacognition. Note that we are only able to estimate the objective criterion because we included catch trials in our hypothetical study. Without the catch trials, it is impossible to estimate an objective criterion[27].

After estimating these three parameters, we construct a curve that represents changes in the object-level sensitivity as a function of relative likelihood of no metacognition. We call this curve the sensitivity vs. metacognition curve (or SvM curve. See Fig. 3c for details of this curve). The x-axis of an SvM curve is the relative likelihood of no metacognition, with zero representing the strongest level of a metacognitive experience. As we move away from zero in this axis, the strength of a metacognitive experience decreases. The y-axis of an SvM curve is object-level sensitivity, with zero representing the chance-level. Moreover, by placing the objective criterion, which is

[27] Using catch trials is not common in metamemory research, and only a handful metamemory studies included catch trials in their design (e.g., Schwartz, 1998; Schwartz et al., 2000).

estimated from the GRT model, we divide the x-axis of an SvM curve into two areas: the area of high likelihood of metacognition, which is to the left of objective criterion, and the area of low likelihood of metacognition, which is in the right of objective criterion. Based on this, we define metacognitive sensitivity as a higher than chance sensitivity in the area of high likelihood of metacognition. Higher than chance sensitivity in the area of low likelihood of metacognition represents memory processes in the absence of metacognition.

In addition to evaluating metacognitive sensitivity of different metacognitive judgments, we can use this model-based analysis to investigate the possibility of an interaction between metacognitive sensitivity of two different metacognitive judgments. For example, we can evaluate the possible influence of experience of TOT on the metacognitive sensitivity of confidence judgments. This type of analysis is quite similar to the GRT-based analysis of metacognitive sensitivity of a metacognitive judgment with only one difference. The y-axis of the SvM curve represents metacognitive sensitivity of the second metacognitive judgment (for example, confidence) measured by meta-d'. That is, such SvM curve represents the metacognitive sensitivity of the second metacognitive judgment (for example, confidence) as a function of relative likelihood of no metacognitive of the first metacognitive judgment (TOT in this example).

Current Study

In the current study, I used the model-based analysis I described in the previous section to evaluate the metacognitive sensitivity of TOTs and FOKs, and to evaluate the influence of TOT and FOK judgments on the metacognitive sensitivity of confidence judgments. At least five decades of research have shown that both TOTs and FOK are associated with increase in the possibility of retrieval of missing information (e.g., Bloom et al., 2018; R. Brown & McNeill, 1966; Chua et al., 2012; Hertzog et al., 2010; Koriat, 1993; Metcalfe et al., 1993; Sacher et al., 2009; Schwartz, 2010; Schwartz et al., 2014; Schwartz & Metcalfe, 1992). However, most of the evidence for the metacognitive sensitivity of these two metacognitive experiences come from studies employing gamma correlation, which we know shows bias (Fleming & Lau, 2014; Masson & Rotello, 2009). In addition, to the best of the author's knowledge, no study has evaluated the influence of TOT and FOK judgments on the metacognitive sensitivity of confidence judgments. That is, it is not clear if confidence judgments more accurately predict performance of the memory recognition task when participants experience a TOT or a high level of FOK.

For these reasons, I advanced two goals in this study. First, I was interested in determining a GRT-based analysis to evaluate the metacognitive sensitivity of TOTs and FOKs. Second, I was interested in evaluating the influence of experiencing a TOT or a high FOK on the metacognitive sensitivity of confidence judgments. To these ends, I adopted a semantic-memory paradigm that allowed me to conduct GRT-based analyses. In two experiments, I presented participants with images of famous faces (Experiment 1) or with general-knowledge questions (Experiment 2). In each trial, if recall failed, participants provided metacognitive judgments of TOT and FOK. Participants then performed a memory recognition task and indicated their confidence about their performance in the recognition task. After collecting the behavioral data in each experiment, I evaluated the metacognitive sensitivity of TOT and FOK using two different SvM curves with memory recognition being the object-level task: an SvM curve to evaluate metacognitive sensitivity of TOT and an SvM curve to evaluate metacognitive sensitivity of FOK. Next, I evaluated the influence of TOT and FOK on the metacognitive sensitivity of confidence using two additional different meta-SvM curves: a meta-SvM curve to evaluate the influence of experiencing a TOT on metacognitive sensitivity of confidence and a meta-SvM curve to evaluate the influence of experiencing a high FOK on metacognitive sensitivity of confidence.

I also conducted two types of complementary analyses to provide a better understanding in regards to metacognitive sensitivities of TOT and FOK and the influence of TOT and FOK on confidence judgment. In the first analyses, I estimated the metacognitive sensitivities of TOT and FOK using gamma correlation. This will allow me to provide a better insight regarding the metacognitive sensitivity of the two metacognitive judgments. In the second analysis, I estimated the mean confidence ratings for the trials that participants reported experiencing a TOT or a high FOK and compared each with the mean confidence ratings for the trial that participants reported not experiencing a TOT or a low FOK.

Based on the current literature, I proposed the following hypotheses:

1- Experiencing a TOT state is associated with higher memory recognition sensitivity. That is, participants will have a higher memory recognition sensitivity in the area of high likelihood of metacognition or when they are experiencing a TOT.

2- Experiencing a high FOK is associated with higher memory recognition sensitivity. That is, participants will have a higher memory recognition sensitivity in the area of high likelihood of metacognition or when they are experiencing a high FOK.

3- Being in a TOT will enhance metacognitive sensitivity of confidence judgment. That is, metacognitive sensitivity of confidence judgments will be higher in the area of high likelihood of metacognition or when they are experiencing a TOT.

4- Reporting high level of FOK judgment will enhance metacognitive sensitivity of confidence judgments to the recognition task. That is, metacognitive sensitivity of confidence judgments will be higher in the area of high likelihood of metacognition or when they are experiencing a high FOK.

5- Experiencing a TOT will induce higher confidence ratings. That is, mean confidence ratings will be higher in the trials with TOT than the trials without TOT.

6- Experiencing a high level of FOK judgments will induce higher confidence ratings. That is, mean confidence ratings will be higher in the trials that participants reported high level of FOK than those with low level of FOK.

To foreshadow, the results supported all of these hypotheses.

II. Experiment 1

The purpose of Experiment 1 was to evaluate the metacognitive sensitivity of TOT and FOK, and to evaluate the influence of TOT and FOK judgments on the metacognitive sensitivity of post-performance confidence when using famous faces as cues. To this end, I presented photographs of famous people (activists, actors and actresses, athletes, musicians, politicians, etc.) and asked participants to recall their last names and then provide three metacognitive judgments (TOTs, FOKs and confidence) for each image for which they did not recall the name.

Materials and Methods

Participants

A total of 72 undergraduate students from Florida International University (FIU) participated in this experiment (65 female, ages 18-45). I recruited the participants from a pool of psychology undergraduate students through FIU Psychology Research Participants System (SONA) for one credit/hour compensation. Each participant completed three behavioral sessions and received a total of five credits. All of the participants had normal or corrected-to-normal vision and were able to read and write in English fluently. This experiment was conducted in accordance with the Declaration of Helsinki, and the Institutional Review Board of Florida International University approved it. Prior to the start of the experiment, participants consented to participate in this study.

Stimuli

I used a total of 400 photographs of famous people (200 male and 200 female) taken from "Celebrity Face Recognition Dataset" (https://github.com/prateekmehta59/Celebrity-

Face-Recognition-Dataset). Each photograph was cropped in a way such that only the face, part of the head, and the neck of the person were visible. I did this to eliminate any non-facial indicators of the name and fame of the faces. In addition, I resized each photograph to be more consistent in size. The final width of all of the photographs were 200 pixels but the height of photographs varied. I also used 200 photographs of non-famous people (100 male and 100 female) for catch trails (see below). I gathered these photographs by searching in Google. I only used images that have "Creative Commons License". Similar to the famous photographs, I cropped and resized non-famous photographs to eliminate any signs that may indicate that the people are not famous.

Behavioral Tasks

This experiment consisted of 600 trials, which were completed in three sessions. In each trial, I presented a photograph of a person who was either famous or non-famous and asked participants to perform a series of five tasks. Below is the description of each task.

Memory Recall

At the beginning of each trial, I presented a photograph of a person and asked participants to recall the last name of that person. Participants were required to type the last name with uppercase letters. If participants did not know the last name, they could leave the answer space blank. Correct recall of a name resulted in termination of the trial and initiation of the next trial. If recall failed, a participant performed the follow-up tasks that I describe next.

TOT and FOK Tasks

If memory recall failed for the name of the person in the photograph, I asked participants to perform the TOT and FOK tasks. In the TOT task, participants indicated if they were experiencing a TOT for the unrecalled item. This was a forced-choice task with two alternatives: “Yes” and “No”. I provided the following definition of TOT to participants: “A tip-of-the-tongue state (or TOT in short) is the feeling that we are about to recall (or remember) something that we actually cannot recall at the moment. For example, if you cannot recall the capital of the United States at the moment but you have the urgent feeling that you are about to recall it at any moment.”

In the FOK task, participants indicated if they had a high or low level of FOK. This was a forced-choice task with two alternatives: “High” and “Low”. I provided the following definition of FOK to participants: “A feeling of knowing is the feeling that you will correctly recognize the correct answer when you see it. For example, you have a high feeling of knowing regarding the capital of the United States if you feel that you can correctly recognize the city when you see its name. You have a low feeling of knowing regarding the capital of the United States if you feel that you cannot correctly recognize the city when you see its name.” It is important to note that participants were not able to see the images while performing the TOT and FOK tasks. Moreover, participants were required to perform these two tasks when recall failed, and the participants could not escape them.

Memory Recognition Task

After indicating the levels of TOT and FOK, I asked participants to perform a memory recognition task. In this task, I presented the target photograph again and provided participants with a last name that was either correct or incorrect. In half of the trials, I presented the correct last name, and in the other half of the trials I presented an incorrect last name. This created two recognition conditions: correct recognition condition (in which

I presented a correct last name) and incorrect recognition condition (in which I presented an incorrect last name). Then, I asked participants to indicate if they think that the provided last name was correct or incorrect using a forced-choice task with two alternatives: “Correct” and “Incorrect.” Regardless of the condition, in the memory recognition task, participants were required to choose one of the alternatives, even if they did not know the correct name.

Confidence Judgment

At the end of each trial, participants rated their confidence on their performance in the memory recognition task as a measure of retrospective metacognition. Participants used one of the following alternatives to rate their confidence in each trial: “very confident”, “somewhat confident”, “a little confident”, and “not at all confident.”

Catch Trials

An important and novel aspect of this experiment was the presence of the catch trials. In this experiment, I defined catch trials as the trials that are composed of photographs of non-famous people. Because these people are not famous, participants will not know their last names, and they should not experience a high level of metacognition (TOT and high FOK) for such photographs, nor is there a known correct answer in recognition. I included the catch trials in the design, to be able to perform model-based analysis based GRT (see the section titled GRT-based Analysis of Metacognitive Sensitivity). But it is also interesting to determine if people will have illusory TOTs or illusory FOKs for novel faces (Schwartz, 1998).

Procedure

This experiment was conducted online, using the Qualtrics platform (fiu.qualtrics.com). Participants were instructed to do the experiment on a computer or a tablet, but not on a phone. Each trial started with the presentation of the target photograph, and participants were asked to recall the last name of the identity of the photograph (memory recall task). Participants typed in the last name with uppercase letters. Correct recall of a name resulted in termination of the trial and initiation of the next trial. If recall failed, a participant answered the follow-up tasks. In this case, I asked them to indicate if they have a TOT experience and if they have high or low level of FOK. Next, we presented the target photograph again, and participants performed the memory recognition task. Finally, participants rated their confidence on their recognition performance. Note that participants could not see the image while performing TOT, FOK and confidence rating tasks but did during recall and recognition.

Each participant completed a total of three sessions with the maximum interval of 20 days between the first and the third sessions. At the beginning of each session, participants received instructions, which contained the definitions of TOT and FOK, and instructions for completing each task. I repeated the instructions in each session to ensure that participants remember the exact instructions and definitions. Sessions one and two were composed of seven blocks each, and session three was composed of six blocks. Each block contained 30 trials. Out of these 30 trials, 10 were correct recognition trials (trials with correct recognition condition), 10 were incorrect recognition trials (incorrect recognition condition), and 10 were catch trials. The order of trials within each block and the order of blocks within each session were randomized.

The order of which came first, the TOT judgments or the FOK judgments, was balanced across blocks to avoid order effects. To this end, the order of TOT and FOK was fixed within each block, but it changed from one block to the next. In session one, four blocks were the ones with TOT first and FOK second (TOT blocks), and three blocks were the ones with FOK first and TOT second (FOK blocks). In session two, four blocks were FOK blocks, and three were TOT blocks. And in session three, three blocks were TOT blocks, and three blocks were FOK blocks. Because I randomized the order of the blocks within each session, it is possible that a TOT block was followed by another TOT block. It is also possible that an FOK block was followed by another FOK block.

Analysis

In order to evaluate metacognitive sensitivity of TOT and FOK, and the possible influence of these two metacognitive judgments on metacognitive sensitivity of confidence judgments, I performed total of eight analyses. For all of the analyses, I used R v. 3.6.3 extended with the package grtools v.0.3.1 (Pournaghdali et al., in revision; Soto et al., 2017). Before discussing the analyses that I performed in this experiment, it is crucial to describe the following in details: the GRT model fitted to data, the fitting procedure, the procedure used to obtain SvA curves, and the parametric bootstrap procedure used to obtain 95% confidence intervals.

GRT-based Analysis of Metacognitive Sensitivity

I fit a special case of GRT model to my data which is called GRT-wIND (Soto et al., 2015). GRT-wIND is a multi-level model, with "group parameters" representing aspects of cognitive processing considered to be common to all participants in an experiment, and “individual parameters” representing aspects of cognitive processing and decision making considered to vary across individuals.

In this study, the task involved three stimulus conditions: correct recognition condition (in which I presented a correct last name in the memory recognition task), incorrect recognition condition (in which I presented an incorrect last name in the memory recognition task) and catch trials. The “group parameters” in GRT-wIND are comprised of three bivariate normal distributions, each representing one of these three conditions. Hence, these three stimulus conditions, indexed by s, each represented by a bivariate normal distribution described by a mean vector:

$$\mu_s = \begin{bmatrix} \mu_{s,x} \\ \mu_{s,y} \end{bmatrix} \qquad (5)$$

And a covariance matrix:

$$\Sigma_s = \begin{bmatrix} \sigma^2_{s,x} & \rho_s \sigma_{s,x} \sigma_{s,y} \\ \rho_s \sigma_{s,x} \sigma_{s,y} & \sigma^2_{s,y} \end{bmatrix} \qquad (6)$$

where *x* is the first dimension of the model, representing memory recognition, *y* is the second dimension of the model, representing metacognition (TOT or FOK), σ is a standard deviation parameter and ρ is a correlation parameter. In order to fix the position of the final solution, I set μ_{noise}= [0,0], and to fix the scale of the final solution, I set $\sigma_{noise,\ x}=\sigma_{noise,\ y}=1$. In theory, this is sufficient to fix the scale of the final solution, and the model assuming equal unit variances performs well without overfitting. Moreover, some researchers have voiced concerns regarding the recoverability of variance parameters from GRT-wIND and the identifiability of the model without fixed variances (Silbert & Thomas, 2017).

The model also includes several individual parameters. Two parameters, κ_k and λ_k, determine the level of attention that participant k allocates to each dimension. The parameter κ_k>0 represents global attention, with high values of it decreasing all variances in the model, which yields better discrimination in both dimensions. The parameter λ_k represents selective dimensional attention, and ranges from 0 to 1. A value of λ_k = 0.5 represents equal attention to both dimensions, with higher values representing more attention to dimension x and lower values representing more attention to dimension y. The covariance matrix for the distribution of cognitive effects of stimulus s in participant k is described by the following equation:

$$\Sigma_{\mathrm{sk}} = \begin{bmatrix} \frac{\sigma_{s,x}^2}{\kappa_k \lambda_k} & \rho_s \frac{\sigma_{s,x}^2 \sigma_{s,y}^2}{\sqrt{\kappa_k^2 \lambda_k (1-\lambda_k)}} \\ \rho_s \frac{\sigma_{s,x}^2 \sigma_{s,y}^2}{\sqrt{\kappa_k^2 \lambda_k (1-\lambda_k)}} & \frac{\sigma_{s,y}^2}{\kappa_k (1-\lambda_k)} \end{bmatrix} \quad (7)$$

The model also assumes individual linear decision bounds or criteria unique to each participant. These individual decision bounds are described by a set of individual parameters. We can write each bound as a discriminant function:

$$h_{dk}(X,Y)=b_{dk,x}X+b_{dk,y}Y+c_{dk} \quad (8)$$

where d indexes a particular discrimination (e.g., d =correct/incorrect, or d =high level of metacognition/low level of metacognition), and X and Y represent specific values in the dimensions x and y, respectively. One parameter in Equation 8 is always fixed to 1. The other two parameters control the slope of the decision bound and its position. In the current application, I assumed that all bounds are orthogonal by fixing the slope parameters to 0 (i.e., an assumption of decisional separability; see Ashby & Soto, 2015; Pournaghdali et al., in revision). GRT-wIND does not require this assumption, but it makes interpretation of individual decision bounds in SvM curves more straightforward. In this case, the decision bounds are equivalent to the decision criteria usually obtained by researchers in data analyses performed using univariate signal detection theory.

Decision bounds divide the two-dimensional space of the model into response regions. Assume that $R_1, R_2, \ldots, R_n$ represent the n possible combinations of responses in an experiment. For example, R_1 could correspond to the response combination "low level of a metacognition (e.g., low FOK) / incorrect recognition", R_2 to the response combination "low level of a metacognition (e.g., low FOK) / correct recognition", R_3 to the response combination "high level of a metacognition (e.g., high FOK) / incorrect recognition", and R_4 to the response combination "high level of a metacognition (e.g., high FOK) / correct recognition". Then the probability of each response combination given the presentation of stimulus *s*, or $P(R_j|s)$, is the area of the distribution representing *s* that falls within the response region assigned to R_j.

We can estimate the parameters of the GRT-wIND model by maximizing the log-likelihood of the model:

$$LL = \sum_k \sum_s \sum_j r_{ksj} \log P(R_j|s), \quad (9)$$

where r_{ksj} represents the frequency with which participant k reported the response combination R_j when presented with stimulus s, and $P_k(R_j|s)$ is the model prediction of the probability of such event.

After fitting the GRT-wIND to the data, we can estimate two parameters for every value of metacognition along the y axis (metacognition dimension) of the GRT model: the relative likelihood of no metacognition and the sensitivity in the object-level task. These two parameters can be used to perform an analysis of the interaction between object-level processing in the object-level task (i.e., memory recognition task) and metacognition. The main product of this analysis is a sensitivity versus metacognition (SvM) curve. Below I describe how to estimate each of these two parameters.

Conditional Sensitivity

Estimation of a GRT-wIND model results in three memory distributions: (1) a noise distribution, with means $\mu_{noise,x}$ and $\mu_{noise,y}$ both fixed to zero, standard deviations $\sigma_{noise,x}$ and $\sigma_{noise,y}$, both fixed to one, and correlation ρ_{noise} that is estimated; (2) an incorrect recognition distribution, with means $\mu_{incorrect,x}$ and $\mu_{incorrect,y}$, standard deviations $\sigma_{incorrect,x}$ and $\sigma_{incorrect,y}$, and correlation $\rho_{incorrect}$, all of them estimated; and (3) a correct recognition distribution, with means $\mu_{correct,x}$ and $\mu_{correct,y}$, standard deviations $\sigma_{correct,x}$ and $\sigma_{correct,y}$, and correlation $\rho_{correct}$, all of them estimated.

These parameters allow one to obtain the distribution of memorial evidence in the memory recognition task, x, conditional on a specific value of metacognition, y=Y, for each stimulus s (i.e., noise, incorrect, and correct), which follows a normal distribution with mean:

$$\mu_{x|y=Y,s}=\mu_{s,x}+\frac{\sigma_{s,x}}{\sigma_{s,y}}\rho_s(Y-\mu_{s,y}), \tag{10}$$

And variance:

$$\sigma^2_{x|y=Y,s}=(1-\rho^2_s)\sigma^2_{x,y}. \tag{11}$$

This allows us to compute object-level value sensitivity conditional on metacognition evidence:

$$d'_{x|y=Y}=\frac{\mu_{x|y=Y,correct}-\mu_{x|y=Y,incorrect}}{\sqrt{\frac{\sigma^2_{x|y=Y,correct}+\sigma^2_{x|y=Y,incorrect}}{2}}}. \tag{12}$$

Note that this is not a single value, but rather a function of *y*.

Relative Likelihood of No Metacognition

Metacognition is not measured as a dichotomy in this model, but rather depends on a graded variable *y*. Using the estimated GRT-wIND model, we can compute an index of the relative likelihood of no metacognition as a function of *y*=Y. For each stimulus *s*, one can obtain a marginal distribution of *y* represented by $g_s(y)$, which is a univariate normal distribution with mean $\mu_{x,y}$ and standard deviation $\sigma_{x,y}$. The condition in which no stimulus is presented is represented by the noise distribution in the GRT model, with marginal $g_{noise}(y)$. This provides an objective benchmark of the area of y where there should be little evidence of metacognition.

The two conditions in which a stimulus is presented, represented by the incorrect and correct distributions in the GRT model, indicate the area in the y-axis where metacognition becomes more likely. Their marginal distributions are represented by

$g_{incorrect}(y)$ and $g_{correct}(y)$. The ratio between the distributions corresponding to these noise and stimulus conditions provides the relative likelihood of no metacognition, or RLNM:

$$\text{RLNM}(y)=\frac{1}{2}\left(\frac{g_{noise}(y)}{g_{incorrect}(y)}+\frac{g_{noise}(y)}{g_{correct}(y)}\right) \quad (13)$$

Note that this is not a single value, but a function of y. For two reasons, the RLNM is a good choice to quantify level of metacognition in the model. First, this measure is easy to interpret: it describes the odds that a high level of a metacognitive experience (e.g., high FOK) should occur versus that a low level of a metacognitive experience (e.g., low FOK) should occur in a trial. Second, this measure provides an objective boundary between areas of high and low likelihood of metacognition, at the value of one. An optimal metacognitive observer whose task is to indicate whether they are experiencing a low or a high level of a metacognitive experience would respond "high" for RLNM < 1 and respond "low" for RLNM > 1. This is an objective benchmark of where there should be a boundary between high- and low-metacognitive processes.

After computing conditional d′ using equation 12 and relative likelihood of no awareness using equation 13 for a range of values of y, we can plot the corresponding values in an SvM curve. One problem is deciding the range of values of y to plot. Because all variances are fixed to one in the model, y is in units of the standard normal distribution. We can plot from the highest mean +2 to the lowest mean -2. This ensures that only a small fraction (less than 5%) of the densities is not covered, without over-extending the range of the plot to areas of the underlying variables unlikely to affect overt psychophysical performance.

Because the GRT-wIND parameter estimates are noisy, the SvM curve computed from them must be noisy as well. To reach conclusions about the interaction between memory processing and metacognition, one must obtain some measure of the uncertainty regarding the curve's position. To do this, I computed confidence intervals using a parametric bootstrap and plotted them in the SvM curve. At each step of the bootstrap, a simulated data set was sampled from the fitted GRT-wIND model and was used to fit a new model to the simulated data. The obtained parameters were used to compute an SvM curve whose values were recorded, and the process started again. A total of 1,000 SvM curves were generated this way, and the resulting empirical distribution of SvM curves was used to obtain 95% confidence intervals at each point of the RLNM variable using a simple quantile procedure. The resulting SvM plots (see Fig. 3c) provide information about the interaction between memory processing in the recognition task and metacognition. A flat function would indicate that memory processing is independent from metacognition. On the other hand, a decreasing or increasing function indicates that memory processing depends on metacognition. We can use the confidence bands to conclude whether the curve deviates from a flat pattern. If the initial and final confidence intervals do not overlap, then one can confidently conclude that the curve is not flat, and memory processing depends or interacts with metacognition.

Similarly, one can use the confidence interval at a value of RLNM = 1 to make conclusions about whether or not memory processes happen in the absence of metacognition. If the confidence interval is at or below zero for all RLNM ≥ 1, this means that there is no memory processing in the absence of metacognition. On the other hand, if the confidence interval is higher than zero at any RLNM ≥ 1, this means that there is memory processing in the absence of metacognition (i.e., memory processing that is present during low likelihood of metacognition). Another possibility is that the curve is increasing, with memory processing being better under conditions of low level of metacognition. In that case, we would expect a positive curve that is not above zero at RLNM < 1, but becomes higher than zero at RLNM ≥ 1, providing evidence for memory processing only in the absence of metacognition (i.e., processing present only during low metacognition, but not present during high metacognition).

GRT-Based Analysis of Metacognitive Sensitivity of TOT

First, I was interested to evaluate metacognitive sensitivity of TOTs. That is, my goal was to accurately determine the extent to which TOTs are associated with increase in the possibility of retrieval of missing information. To this end, I fit a GRT-wIND model (Soto et al., 2015) to the behavioral data, with TOT and memory recognition being the dimensions of interest. I used maximum likelihood estimation to fit a GRT-wIND model to the data. To make sure that the fitted model included the true maximum likelihood parameter estimates, I ran the optimization algorithm 100 times, each time starting from a different random configuration of starting parameters, and I kept the model with the highest likelihood. Figure 3b presents a schematic representation of the fitted GRT model. The y-axis of the GRT model represents metacognition of the stimulus, which are TOTs in this analysis. Zero in this axis represents no metacognition and as we move away from zero, the intensity of metacognition increases, meaning the intensity of TOT experience increases. The x-axis represents stimulus value along the memory recognition dimension.

In Experiment 1, there were three stimulus conditions: correct recognition condition, incorrect recognition condition and catch trials. Each stimulus condition (correct, incorrect and catch trials) is represented by a bidimensional normal distribution, represented by an ellipse in the figure 3b. The bidimensional distribution that represent catch trials is represented by an ellipse that is centered at zero in both dimensions of metacognition and memory recognition. The other two stimuli (correct and incorrect) are represented by two bidimensional distributions, higher in the metacognition dimension in the y-axis and away from zero in opposite directions along the x-axis, corresponding to opposite memory recognition conditions.

After fitting the GRT model to the data, I estimated two parameters that were conditional to the value of metacognition in the y-axis. The first parameter, is "the relative likelihood of no metacognition," that is the result of dividing the likelihood of high level of metacognition, by likelihood of low level of metacognition. At zero in the y-axis "the relative likelihood of no metacognition" is at the highest and as we move away from zero "the relative likelihood of no metacognition" decreases. The second parameter is the conditional sensitivity (d'; see Green & Swets, 1966; Macmillan & Creelman, 2005) in the memory recognition as a function of the value of metacognition in the y-axis.

After estimating the relative likelihood of no metacognition and sensitivity for every value of metacognition on the y-axis of the GRT model, I constructed an SvM curve (Fig. 3c). The y-axis of the SvM curve represents conditional sensitivity of the memory recognition task. Zero in this axis represents chance level, and as we move away from zero, the sensitivity increases. The x-axis of the SvM curve represent relative likelihood of no metacognition. Zero represents the lowest relative likelihood of no metacognition, and it indicates the highest level of metacognition. As we move away from zero, the relative likelihood of metacognition increases, meaning that metacognitive experiences lose their strength. The vertical orange line is the objective criterion based on the optimal observer in the GRT model. This is the point in the x-axis of the SvM curve where the likelihood of high level of metacognition equals the likelihood of low level of metacognition. This optimal criterion divides the x-axis of the SvM curve into two areas: the area of low and high likelihood of metacognition. The red line is the SvM model extracted from the GRT model.

I was also interested in obtaining 95% confidence interval for the extracted SvM curve. To this end, I generated 1,000 simulated data samples from the fitted GRT model. Then, I fit the model to each data sample again and obtained the SvM curve as indicated above. The result of this process is an empirical distribution function for SvM curves. I reported the simple percentiles from this function as limits for the 95% confidence interval, which is represented by the lighter red bands in the figure 4b.

GRT-Based Analysis of Metacognitive Sensitivity of FOK

Next, I was interested in evaluating metacognitive sensitivity of FOKs. That is, my goal was to accurately determine the extent to which FOKs are associated with increase in the possibility of retrieval of missing information. To this end, I fit a GRT-wIND model (Soto et al., 2015) to the behavioral data, with FOK and memory recognition being the dimensions of interest. I used maximum likelihood estimation to fit a GRT-wIND model to the data. To make sure that the fitted model included the true maximum likelihood parameter estimates, I ran the optimization algorithm 100 times, each time starting from a different random configuration of starting parameters, and I kept the model with the highest likelihood. Figure 3b presents a schematic representation of the fitted GRT model. The y-axis of the GRT model represents metacognition of the stimulus, which are FOKs in this analysis. Zero in this axis represents no metacognition, and as we move away from zero, the intensity of metacognition increases, meaning the intensity of FOK experience increases. The x-axis represents stimulus value along the memory recognition dimension.

In Experiment 1, there were three stimulus conditions: correct recognition condition, incorrect recognition condition and catch trials. Each stimulus condition (correct, incorrect and catch trials) is represented by a bidimensional normal distribution, represented by an ellipse in the figure 3b. The bidimensional distribution that represent catch trials is represented by an ellipse that is centered at zero in both dimensions of metacognition and memory recognition. The other two stimuli (correct and incorrect) are represented by two bidimensional distributions, higher in the metacognition dimension in the y-axis and away from zero in opposite directions along the x-axis, corresponding to opposite memory recognition conditions.

After fitting the GRT model to the data, I estimated two parameters that were conditional to the value of metacognition in the y-axis. The first parameter, is "the relative likelihood of no metacognition," that is the result of dividing the likelihood of high level of metacognition, by likelihood of low level of metacognition. At zero in the y-axis "the relative likelihood of no metacognition" is at the highest and as we move away from zero "the relative likelihood of no metacognition" decreases. The second parameter is the conditional sensitivity (d'; see Green & Swets, 1966; Macmillan & Creelman, 2005) in the memory recognition as a function of the value of metacognition in the y-axis.

After estimating the relative likelihood of no metacognition and sensitivity for every value of metacognition on the y-axis of the GRT model, I constructed an SvM curve (Fig. 3c). The y-axis of the SvM curve represents conditional sensitivity of the memory recognition task. Zero in this axis represents chance level, and as we move away from zero, the sensitivity increases. The x-axis of the SvM curve represent relative likelihood of no metacognition. Zero represents the lowest relative likelihood of no metacognition, and it indicates the highest level of metacognition. As we move away from zero, the relative likelihood of metacognition increases, meaning that metacognitive experiences lose their strength. The vertical orange line is the objective criterion based on the optimal observer in the GRT model. This is the point in the x-axis of the SvM curve where the likelihood of high level of metacognition equals the likelihood of low level of metacognition. This optimal criterion divides the x-axis of the SvM curve into two areas: the area of low and high likelihood of metacognition. The red line is the SvM model extracted from the GRT model.

I was also interested in obtaining 95% confidence interval for the extracted SvM curve. To this end, I generated 1,000 simulated data samples from the fitted GRT model. Then, I fit the model to each data sample again and obtained the SvM curve as indicated above. The result of this process is an empirical distribution function for SvM curves. I reported the simple percentiles from this function as limits for the 95% confidence interval, which is represented by the lighter red bands in the figure 4d.

Evaluating the Metacognitive Sensitivity of TOT Using Gamma Correlation

I was also interested to determine if there is a compatibility between the results of the SvM analysis of metacognitive sensitivity of TOT and the results from a traditional and popular measure of metacognitive sensitivity: gamma correlation (e.g., Bloom et al., 2018; A. Brown, 1991; Schwartz, 2010). Accordingly, I estimated a gamma coefficient that represents the correlation between experience of TOT and accuracy of participants in the memory recognition task.

To this end, I summarized participants' TOT responses based on the accuracy of their responses in the memory recognition task in a two-by-two frequency table that I describe below (see Table 2). In this frequency table, the four response cells represent four categories of type 2 responses: hit, false alarm, miss and correct rejection. A type 2 hit happens when a participant responds correctly to the memory recognition task and also reports experiencing a TOT (H2). A type 2 false alarm happens when a participant responds incorrectly to the memory recognition task but reports experiencing a TOT (FA2). A type 2 miss happens when a participant responds correctly to the memory recognition task but reports not experiencing a TOT (M2). Finally, a type 2 correct rejection happens when a participant responds incorrectly to the memory recognition task and also reports not experiencing a TOT (CR2).

Table 2 Classification of TOT responses based on type 1 accuracy.

	Correct Recognition	**Incorrect Recognition**
TOT	Hit	False Alarm
No TOT	Miss	Correct Rejection

Based on this, I defined hit rate (HR2) and false alarm rate (FAR2) based on the equations 1 and 2 respectively (see the section titled How to Measure Metacognition). Then, by plugging HR2 and FAR2 into the equation 3, I estimated the gamma coefficient (see the section titled How to Measure Metacognition). After estimating gamma coefficient, I contrasted it against the chance level (zero). In this analysis, higher than chance gamma coefficient represents the presence of metacognitive sensitivity of TOT, meaning that experiencing a TOT indeed increases the possibility of correct retrieval of item in a memory recognition task. On the other hand, chance level gamma coefficient represents the absent of metacognitive sensitivity of TOT, meaning that experiencing a TOT has no influence on the possibility of correct retrieval of item in a memory recognition task.

Evaluating the Metacognitive Sensitivity of FOK Using Gamma Correlation

I was also interested to determine if there is a compatibility between the results of the SvM analysis of metacognitive sensitivity of FOK and gamma correlation results (e.g., Hertzog et al., 2010; Nelson et al., 1982). Accordingly, I estimated a gamma coefficient that represents the correlation between experience of FOK and accuracy of participants in the memory recognition task.

To this end, I summarized participants' FOK responses based on the accuracy of their responses in the memory recognition task in a two-by-two frequency table that I describe below (see Table 3). In this frequency table, the four response cells represent four categories of type 2 responses: hit, false alarm, miss and correct rejection. A type 2 hit happens when a participant responds correctly to the memory recognition task and also reports experiencing a high FOK (H2). A type 2 false alarm happens when a participant responds incorrectly to the memory recognition task but reports experiencing a high FOK (FA2). A type 2 miss happens when a participant responds correctly to the memory recognition task but reports not experiencing a low FOK (M2). Finally, a type 2 correct rejection happens when a participant responds incorrectly to the memory recognition task and also reports not experiencing a low FOK (CR2).

Table 3 Classification of FOK responses based on type 1 accuracy.

	Correct Recognition	**Incorrect Recognition**
High FOK	Hit	False Alarm
Low FOK	Miss	Correct Rejection

Based on this, I defined hit rate (HR2) and false alarm rate (FAR2) based on the equations 1 and 2 respectively (see the section titled How to Measure Metacognition). Then, by plugging HR2 and FAR2 into the equation 3, I estimated the gamma coefficient. After estimating gamma coefficient, I contrasted it against the chance level (zero). In this analysis, higher than chance gamma coefficient represents the presence of metacognitive sensitivity of FOK, meaning that experiencing a high FOK indeed increases the possibility of correct retrieval of item in a memory recognition task. On the other hand, chance level gamma coefficient represents the absent of metacognitive sensitivity of FOK, meaning that experiencing a high FOK has no influence on the possibility of correct retrieval of item in a memory recognition task.

GRT-Based Analysis of Influence of TOT on Metacognitive Sensitivity of Confidence

One of the main aims of this study was to evaluate the influence of TOT on the metacognitive sensitivity of confidence judgments. That is, I was interested to determine if experiencing a TOT increases the metacognitive sensitivity of confidence judgments. Therefore, the measure of interest in this analysis was the metacognitive sensitivity of confidence (meta-d'; Maniscalco & Lau, 2012, 2014). Hence, I was interested to know if meta-d' depends on the relative likelihood of no metacognition (TOT in this analysis). To this end, I collapsed participants' confidence ratings on their memory recognition responses as follow: I collapsed "very confident" and "somewhat confident" responses in one category (Confident). Then, I classified "a little confident" and "not at all confident" responses in the second category (Not-Confident). I did this to ensure that I had enough data points in each response category to allow for model fitting.

The analysis of confidence ratings proceeded exactly as the analysis of data from the main memory recognition task. The only difference was that the GRT model fitted to data included two response criteria for the "memory recognition" dimension, one of them separating "confident incorrect" responses from "not-confident" responses, and the other separating "not-confident" responses from "confident correct" responses. Our team previously proposed that the GRT-based analysis of confidence judgments is theoretically related to the meta-d' measure proposed by Maniscalco and Lau (2012, 2014; see Pournaghdali et al., in revision). Similar to meta-d' proposed by Maniscalco and Lau (2012, 2014), I obtained the conditional meta-d' in this SVM curve by determining what d' could explain the confidence data under the same distributional assumptions used to compute d' from discrimination data. For this reason, I call this specific type of GRT, meta-GRT, and I call the SvM curve extracted from the meta-GRT the meta-SvM curve.

GRT-Based Analysis of Influence of FOK on Metacognitive Sensitivity of Confidence

Another aim of this study was to evaluate the influence of FOK on the metacognitive sensitivity of confidence ratings. That is, I was interested to see if a high FOK increases the metacognitive sensitivity of confidence ratings. To this end, I performed a similar GRT analysis as the meta-GRT analysis described in the previous section, with only one difference: The y-axis of the meta-GRT model in the current analysis represents FOK. As the meta-GRT analysis of TOT, the measure of interest in this analysis was the metacognitive sensitivity of confidence (meta-d'; Maniscalco & Lau, 2012, 2014). I was interested in determining if meta-d' depends on the relative likelihood of no metacognition (FOK in this analysis). To this end, I collapsed participants' confidence ratings on their memory recognition responses as follow: I collapsed "very confident" and "somewhat confident" responses in one category (Confident). Then, I classified "a little confident" and "not at all confident" responses in the second category (Not-Confident). I did this to ensure that I had enough data points in each response category to allow for model fitting.

The analysis of confidence ratings proceeded exactly as the analysis of data from the main memory recognition task. The only difference was that the meta-GRT model fitted to data included two response criteria for the "memory recognition" dimension, one of them separating "confident incorrect" responses from "not-confident" responses, and the other separating "not-confident" responses from "confident correct" responses. Similar to meta-d' proposed by Maniscalco and Lau (2012, 2014), I obtained the conditional meta-d' in this meta-SVM curve by determining what d' could explain the confidence data under the same distributional assumptions used to compute d' from discrimination data.

Evaluating the influence of TOT on average confidence rating

Next, I was interested in evaluating the influence of TOT on the average confidence rating provided by participants. For this reason, I calculated each participant's average confidence ratings in the trials that they reported experiencing a TOT (TOT trials) and the trials that they reported not experiencing a TOT (No-TOT trials). Then, I performed a

Friedman test to compare average confidence rating between the TOT trials and the No-TOT trials. I chose Friedman test, because average confidence scores were not normally distributed (i.e., violation of normality).

Evaluating the influence of FOK on average confidence rating

Finally, I was interested in evaluating the influence of FOK on the average confidence rating provided by participants. For this reason, I calculated each participant's average confidence ratings in the trials that they reported experiencing a high FOK (high-FOK trials) and the trials that they reported experiencing a low FOK (low-FOK trials). Then, I performed a Friedman test to compare average confidence rating between the high-FOK trials and the low-FOK trials. I chose Friedman test, because average confidence scores were not normally distributed (i.e., violation of normality).

Results

On average, participants recalled 29.39 percent of the last names correctly in the memory recall task. Moreover, on average participants reported a TOT in 29.03 percent (N=78.68) of the unrecalled trials (i.e., trials that participants could not recall the last names correctly) and high FOK in 33.09 percent (N=90.53) of the unrecalled trials. Moreover, participants reported experiencing a TOT in 0.05 percent (N=9.79) and FOK in 0.05 percent (N=10.19) of the catch trials. Participants also achieved an average of 64.45 percent accuracy in the memory recognition task in the unrecalled trials, which was significantly higher than chance-level (one sample t-test, $t(71)=63.60$, $p<0.001$).

GRT-Based Analysis of Metacognitive Sensitivity of TOT and FOK

I presented the main results of this section in Figure 4. The figures in the left column (4a and 4c) depict the estimated GRT models for each metacognitive judgment, and the figures in the right column (4b and 4d) depict SvM curves extracted from each model. In all of the SvM curve graphs, the x-axis represents the relative likelihood of no metacognition, with zero representing the strongest level of a metacognitive experience. The y-axis represents sensitivity in the memory recognition task, with zero representing the chance-level. The vertical blue line is the objective criterion based on the optimal observer in the GRT model and the vertical green lines are the individual criterion of participants. The red line is the SvM model extracted from the GRT model. Finally, the lighter red bands represent the 95 percent confidence interval. In the following paragraphs, I present and discuss the results of metacognitive sensitivity of TOT and FOK separately.

Metacognitive Sensitivity of TOT

By accounting for 98.95% of the behavioral data, the estimated GRT model provided a good fit to the data (see Fig. 4a). Figure 4b depicts the SvM curve representing metacognitive sensitivity of TOT. Based on this SvM curve, the sensitivity in the memory recognition task is dependent on the strength of TOT experiences. That is, the sensitivity in the memory recognition task is highest when participants are experiencing a high level of TOT. Accordingly, as the strength of TOT experiences decreases, so does the memory recognition sensitivity. Furthermore, the sensitivity of the memory recognition approaches zero (i.e., chance-level) in the area of low likelihood of metacognition. This indicates the survival of memory recognition processes in the absence of a TOT experience.

In addition, the SvM analysis indicates that participants adopted a conservative metacognitive criterion in comparison to the objective criterion. This means that participants are less likely to report experiencing a TOT even when they likely to be experiencing a metacognitive experience equivalent to a weak TOT state. That is, participants reported experiencing a TOT only if the experience was strong and profound.

Metacognitive Sensitivity of FOK

By accounting for 98.68% of the behavioral data, the estimated GRT model provided a good fit to the data (see Fig. 4c). Figure 4d depicts the SvM curve representing metacognitive sensitivity of FOK. Based on this SvM curve, the sensitivity in the memory recognition task is dependent on the strength of FOK experiences. That is, the sensitivity in the memory recognition task is highest when participants are experiencing a high level of FOK. Accordingly, as the strength of FOK experiences decreases, so does the memory recognition sensitivity. Furthermore, the sensitivity of the memory recognition approaches zero (i.e., chance-level) in the area of low likelihood of metacognition. This indicates the survival of memory recognition processes when participants were experiencing a low level of FOK.

In addition, the SvM analysis indicates that participants adopted a conservative metacognitive criterion in comparison to the objective criterion. This means that participants are less likely to report experiencing a high level of FOK. That is, participants reported experiencing a high level of FOK only if their FOK experience was strong.

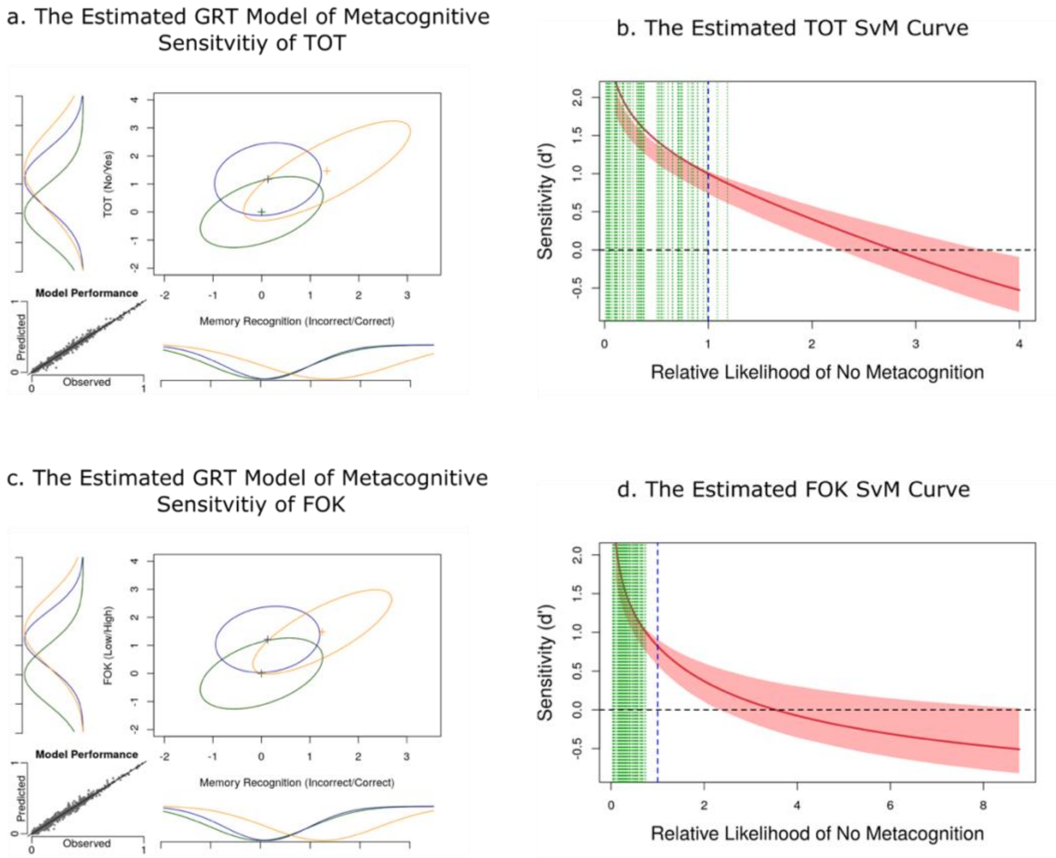

Fig. 4 The Results of GRT-based Analysis of Metacognitive Sensitivity of TOT and FOK in Experiment 1**.** The estimated GRT models of metacognitive sensitivity of TOT and FOK are shown in figure 4a and 4c respectively. In both GRT models, the yellow oval represents bidimensional probability distribution of correct recognition condition, the blue oval represents bidimensional probability distribution of incorrect recognition condition, and the green oval represents bidimensional probability distribution of catch trials. Moreover, the estimated SvM curve representing metacognitive sensitivity of TOT and FOK are shown in figure 4b and 4d respectively. In both SvM curves, the x-axis represents the relative likelihood of no metacognition, with zero representing the strongest level of a metacognitive experience. The y-axis represents sensitivity in the memory recognition task, with zero representing the chance-level. The vertical blue line is the objective criterion based on the optimal observer in the GRT model and the vertical green lines are the individual criterion of participants. The red line is the SvM model extracted from the GRT model, and the lighter red bands represent the 95 percent confidence interval.

Evaluating the Metacognitive Sensitivity of TOT and FOK Using Gamma Correlation

Metacognitive Sensitivity of TOT

Accuracy of performance in a memory recognition task was moderately correlated with TOT (γ=0.465, *standard error*=0.014, *95% CI*=0.437 to 0.493), which was significantly higher than chance-level (Z=30.597*,* p<0.001). This indicates that experiencing a TOT is associated with a higher likelihood of correct recognition performance. This is in line with the results of GRT-based analysis of metacognitive sensitivity of TOT.

Metacognitive Sensitivity of FOK

Accuracy of performance in a memory recognition task was moderately correlated with FOK (γ=0.471, *standard error*=0.013, *95% CI*=0.445 to 0.497), which was significantly higher than chance-level (Z=32.487, p<0.001). This indicates that experiencing a high FOK is associated with a higher likelihood of correct recognition performance. This is in line with the results of GRT-based analysis of metacognitive sensitivity of FOK.

GRT-Based Analysis of The Influence of TOT and FOK on Metacognitive Sensitivity of Confidence

I presented the main results of this section in Figure 5. The figures in the left column (5a and 5c) depict the estimated meta-GRT models for each metacognitive judgment (TOT and FOK), and the figures in the right column (5b and 5d) depict meta-SvM curves extracted from each model. In all of the meta-SvM curve graphs, the x-axis represents the relative likelihood of no metacognition, with zero representing the strongest level of a metacognitive experience. The y-axis represents metacognitive sensitivity of confidence ratings, with zero representing the chance-level. The vertical blue line is the objective criterion based on the optimal observer in the meta-GRT model, and the vertical green lines are the individual criterion of participants. The red line is the meta-SvM model extracted from the meta-GRT model. Finally, the lighter red bands represent the 95 percent confidence interval.

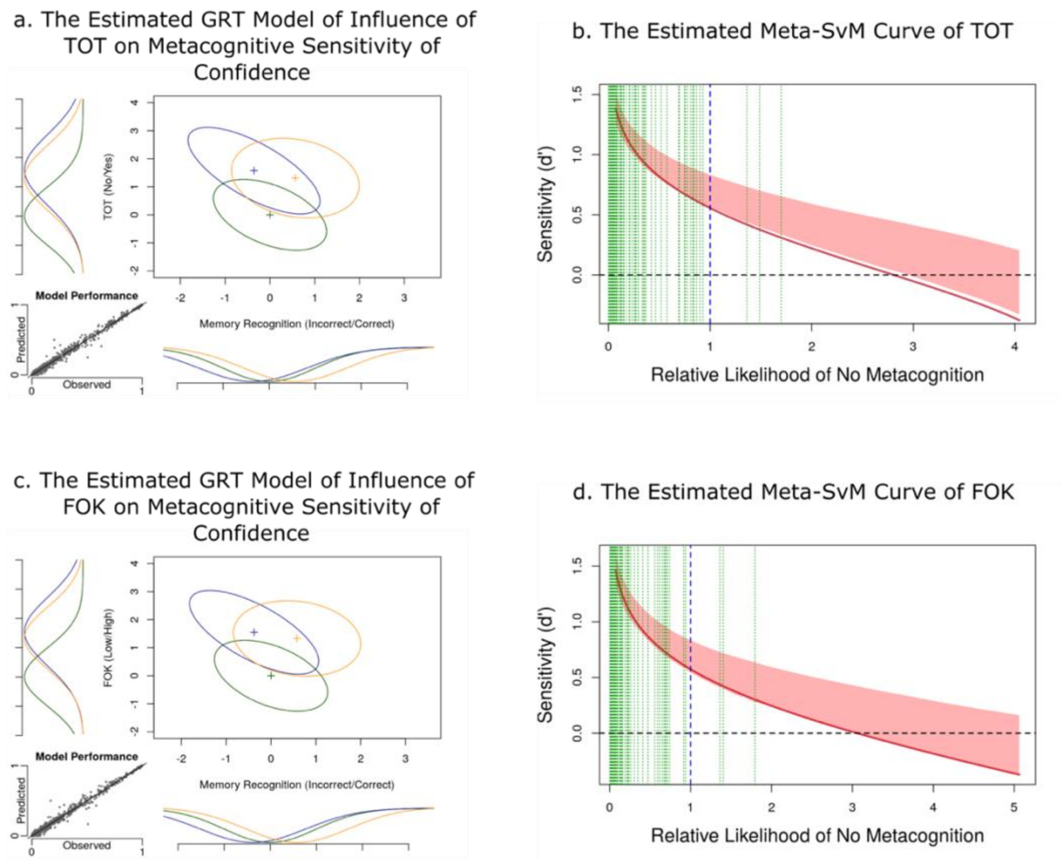

Fig. 5 The Results of GRT-based Analysis of Influence of TOT and FOK on Metacognitive Sensitivity of Confidence in Experiment 1**.** The estimated meta-GRT models are shown in figure 5a and 5c respectively. In both meta-GRT models, the yellow oval represents bidimensional probability distribution of correct recognition condition, the blue oval represents bidimensional probability distribution of incorrect recognition condition, and the green oval represents bidimensional probability distribution of catch trials. Moreover, the estimated meta-SvM curve representing metacognitive sensitivity of TOT and FOK are shown in figure 5b and 5d respectively. In both meta-SvM curves, the x-axis represents the relative likelihood of no metacognition, with zero representing the strongest level of a metacognitive experience. The y-axis represents metacognitive sensitivity of confidence ratings, with zero representing the chance-level. The vertical blue line is the objective criterion based on the optimal observer in the meta-GRT model and the vertical green lines are the individual criterion of participants. The red line is the meta-SvM model extracted from the meta-GRT model, and the lighter red bands represent the 95 percent confidence interval.

The Influence of TOT on Metacognitive Sensitivity of Confidence

By accounting for 99.07% of the behavioral data, the estimated meta-GRT model provided a good fit to the data (see Fig. 5a). Figure 5b depicts the meta-SvM curve representing metacognitive sensitivity of confidence as a function of strength of TOT.

Based on this meta-SvM curve, the metacognitive sensitivity of confidence is dependent on the strength of TOT experiences. That is, the metacognitive sensitivity of confidence is highest when participants are experiencing a high level of TOT. Accordingly, as the strength of TOT experiences decreases, so does the metacognitive sensitivity of confidence. Furthermore, the metacognitive sensitivity of confidence approaches zero (i.e., chance-level) in the area of low likelihood of metacognition. This indicates the survival of confidence-related processes in the absence of a TOT experience.

Similar to the results of GRT-based analysis of TOT, the meta-SvM analysis indicates that participants adopted a conservative metacognitive (TOT) criterion in comparison to the objective criterion. This means that participants are less likely to report experiencing a TOT even when they likely to be experiencing a metacognitive experience equivalent to a weak TOT state. That is, participants reported experiencing a TOT only if the experience was strong and profound.

The Influence of FOK on Metacognitive Sensitivity of Confidence

By accounting for 98.97% of the behavioral data, the estimated meta-GRT model provided a good fit to the data (see Fig. 5c). Figure 5d depicts the meta-SvM curve representing metacognitive sensitivity of confidence as a function of strength of FOK. Based on this meta-SvM curve, the metacognitive sensitivity of confidence is dependent on the strength of FOK experiences. That is, the metacognitive sensitivity of confidence is highest when participants are experiencing a high level of FOK. Accordingly, as the strength of FOK experiences decreases, so does the metacognitive sensitivity of confidence. Furthermore, the metacognitive sensitivity of confidence approaches zero (i.e., chance-level) in the area of low likelihood of metacognition. This indicates the survival of confidence-related processes when participants were experiencing a low level of FOK.

Similar to the results of GRT-based analysis of FOK, the meta-SvM analysis indicates that participants adopted a conservative metacognitive (FOK) criterion in comparison to the objective criterion. This means that participants are less likely to report experiencing a high level of FOK. That is, participants reported experiencing a high level of FOK only if their FOK experience was strong.

Evaluating the Influence of TOT and FOK on Average Confidence Rating

Evaluating the impact of TOT on average confidence rating showed that participants' confidence rating was significantly higher in the trials that they reported experiencing a TOT (*M*=3.08, *SD*=0.522) than the trials that they reported not experiencing a TOT (*M*= 1.48, *SD*=0.415, $\chi^2(1)= 72$, $p<0.001$). Evaluating the impact of FOK on average confidence rating showed that participants' confidence rating was significantly higher in the trials that they reported experiencing a high FOK (*M*= 2.94, *SD*= 0.485) than the trials that they reported experiencing a low FOK (*M*=1.44, *SD*= 0.414, $\chi^2(1)= 72$, $p<0.001$). Hence, experiencing a TOT or a high FOK associates with higher level of confidence.

Discussion

The purpose of Experiment 1 was to evaluate the metacognitive sensitivity of TOT and FOK, and to evaluate the influence of TOT and FOK judgments on the metacognitive sensitivity of post-performance confidence when using famous faces as cues. The results of the GRT-based analyses showed that experiencing TOT and a high FOK are associated with increase in sensitivity in the memory recognition task. That is, the highest level of recognition sensitivity was observed in the area of high likelihood of metacognition and when participants were experiencing the highest level of each metacognitive experience. Gamma correlation analysis also supported these results.

Moreover, the results of the GRT-based analyses showed that experiencing TOT and a high FOK are associated with increase in metacognitive sensitivity of confidence judgments. That is, the highest level of metacognitive sensitivity of confidence was observed in the area of high likelihood of metacognition and when participants were experiencing the highest level of TOT or FOK. The results also indicate that experience of TOT or a high FOK is also associated with higher confidence ratings. Finally, comparing participants' metacognitive bias against the objective criterion showed that participants adopted a conservative metacognitive bias in reporting experiencing a TOT and high FOK. That is, they were less likely to report experiencing a TOT or a high FOK. These results are true for TOTs and FOK for the semantic recollection of famous faces, but it remains to be seen if these data will generalize to other stimuli. Therefore, in the second experiment I replicated these results when participants recalled answers to a series of general-knowledge questions.

III. Experiment 2

The purpose of Experiment 2 was to evaluate the metacognitive sensitivity of TOT and FOK, and to evaluate the influence of TOT and FOK judgments on the metacognitive sensitivity of post-performance confidence when using general-knowledge questions as cues. To this end, I presented general-knowledge questions and asked participants to recall the answers to these questions and provide metacognitive judgments (TOTs, FOKs and confidence) in regards to these questions.

Materials and Methods

Participants

A total of 51 undergraduate students from Florida International University (FIU) participated in this experiment (44 female, ages 18-58). I recruited the participants from a pool of psychology undergraduate students through FIU Psychology Research Participants System (SONA) for one credit/hour compensation (Each participant received 5 credits). All of the participants had normal or corrected-to-normal vision and were able to read and write in English fluently. This experiment was conducted in accordance with the Declaration of Helsinki, and the Institutional Review Board of Florida International University approved it. Prior to the start of the experiment, participants consented to participate in this study.

Stimuli

The target stimuli were composed of 400 general-knowledge questions. Out of 400 questions, 274 questions were extracted from Tauber et al. (2013) updated norm of Nelson and Narens (1980) norm. I did not use the rest of the questions from this norm because the remaining questions had multiple correct answers at the current time. I created the remaining 126 questions (These questions are accessible in Appendix A). I also created 200 questions with no correct answer (non-factual questions) for catch trials (These questions are accessible in Appendix B). Because these questions had no correct answer (for example, what is the Capital of Lagaria?), participants should not know the answers to them, and, ideally, they should not experience a high level of metacognition (TOT and high FOK) for such questions.

Behavioral Tasks

This experiment consisted of 600 trials, which were completed in three sessions. In each trial, I presented a general-knowledge question that were either factual (i.e., having a correct answer. For example, which precious gem is red?) or nonfactual (i.e., not having a correct answer. For example, in what country is “mount Iggrayl” located?) and asked participants to perform a series of five tasks. Below is the description of each task.

Memory Recall

At the beginning of each trial, I presented a question and asked participants to recall the correct answer to that question. Participants were required to type their answer with uppercase letters. If participants did not know the answer, they could leave the answer space blank. Correct recall of an answer resulted in termination of the trial and initiation of the next trial. If recall failed, a participant performed the follow-up tasks that I describe next.

TOT and FOK Tasks

If memory recall failed for the correct answer to the question, I asked participants to perform the TOT and FOK tasks. In the TOT task, participants indicated if they were experiencing a TOT for the unrecalled item. This was a forced-choice task with two alternatives: "Yes" and "No." I provided the following definition of TOT to participants: "A tip-of-the-tongue state (or TOT in short) is the feeling that we are about to recall (or remember) something that we actually cannot recall at the moment. For example, if you cannot recall the capital of the United States at the moment but you have the urgent feeling that you are about to recall it at any moment."

In the FOK task, participants indicated if they had a high or low level of FOK. This was a forced-choice task with two alternatives: "High" and "Low." I provided the following definition of FOK to participants: "A feeling of knowing is the feeling that you will correctly recognize the correct answer when you see it. For example, you have a high feeling of knowing regarding the capital of the United States if you feel that you can correctly recognize the city when you see its name. You have a low feeling of knowing regarding the capital of the United States if you feel that you cannot correctly recognize the city when you see its name." It is important to note that participants were not able to see the questions while performing the TOT and FOK tasks. Moreover, participants were required to perform these two tasks when recall failed, and the participants could not escape them.

Memory Recognition Task

After indicating the levels of TOT and FOK, I asked participants to perform a memory recognition task. In this task, I presented the general-knowledge question again and provided participants with an answer that was either correct or incorrect. In half of the trials, I presented the correct answer, and in the other half of the trials I presented an incorrect answer. This created two recognition conditions: correct recognition condition (in which I presented a correct answer) and incorrect recognition condition (in which I presented an incorrect answer). Then I asked participants to indicate if they thought that the provided answer was correct or incorrect using a forced-choice task with two alternatives: "Correct" and "Incorrect." Regardless of the condition, in the memory recognition task, participants were required to choose one of the alternatives, even if they did not know the correct answer.

Confidence Judgment

At the end of each trial, participants rated their confidence on their performance in the memory recognition task as a measure of retrospective metacognition. Participants used one of the following alternatives to rate their confidence in each trial: "very confident", "somewhat confident", "a little confident", and "not at all confident."

Catch Trials

An important and novel aspect of this experiment was the presence of the catch trials. In this experiment, I defined catch trials as the trials that are composed of nonfactual questions with no correct answer. Because these questions have no correct answer participants will not know their answers, and they should not experience a high level of metacognition (TOT and high FOK) for such questions, nor is there a known correct answer in recognition. I included the catch trials in the design, to be able to perform model-based analysis based GRT (see the section titled GRT-based Analysis of Metacognitive Sensitivity).

Procedure

This experiment was conducted online using the Qualtrics platform (fiu.qualtrics.com). Participants were instructed to do the experiment on a computer or a tablet, but not on a phone. Each trial started with the presentation of the target question, and participants were asked to recall the answer to the target question (memory recall task). Participants typed in the answer with uppercase letters. Correct recall of an answer resulted in termination of the trial and initiation of the next trial. If recall failed, a participant answered the follow-up tasks. In this case, I asked them to indicate if they have a TOT experience and if they have high or low level of FOK. Next, I presented the target question again, and participants performed the memory recognition task. Finally, participants rated their confidence on their recognition performance. Note that participants could not see the question while performing TOT, FOK, and confidence rating tasks but did during recall and recognition.

Each participant completed a total of three sessions with the maximum interval of 20 days between the first and the third sessions. At the beginning of each session, participants received instructions, which contained the definitions of TOT and FOK, and instructions for completing each task. I repeat the instructions in each session, to make sure participants remember the exact instructions and definitions. Sessions one and two were composed of seven blocks each, and session three was composed of six blocks. Each block contained 30 trials. Out of these 30 trials, 10 were correct recognition trials (trials with correct recognition condition), 10 were incorrect recognition trials (incorrect recognition condition), and 10 were catch trials. The order of trials within each block and the order of blocks within each session were randomized.

The order of which came first, the TOT judgments or the FOK judgments, was balanced across blocks to avoid order effect. To this end, the order of TOT and FOK was fixed within each block, but it changed from one block to the next. In session one, four blocks were the ones with TOT first and FOK second (TOT blocks), and three blocks were the ones with FOK first and TOT second (FOK blocks). In session two, four blocks were FOK blocks, and three were TOT blocks. And in session three, three blocks were TOT blocks, and three blocks were FOK blocks. Because I randomized the order of the blocks within each session, it is possible that a TOT block was followed by another TOT block. It is also possible that an FOK block was followed by another FOK block.

Analyses

The analyses performed in Experiment 2 were identical to those of Experiment 1.

Results

On average participants could recall 26.53 percent of the target answers correctly in the memory recall task. Moreover, on average participants reported TOT in 22.25 percent (N=55.63) of the unrecalled trials (i.e., trials that participants could not recall the target answers correctly) and high FOK in 29.22 percent (N=72.24) of the unrecalled trials. Moreover, participants reported experiencing a TOT in 13.51 percent (N=24.20) and FOK in 18.71 percent (N=33.45) of the catch trials. Participants also achieved average of 58.14 percent accuracy in the memory recognition task in the unrecalled trials, which was significantly higher than chance-level (one sample t-test, $t(50) = 73.39$, $p<0.001$).

GRT-Based Analysis of Metacognitive Sensitivity of TOT and FOK

I presented the main results of this section in Figure 6. The figures in the left column (6 a and 6c) depict the estimated GRT models for each metacognitive judgment, and the figures in the right column (6b and 6d) depict SvM curves extracted from each model. In all of the SvM curve graphs, the x-axis represents the relative likelihood of no metacognition, with zero representing the strongest level of a metacognitive experience.

The y-axis represents sensitivity in the memory recognition task, with zero representing the chance-level. The vertical blue line is the objective criterion based on the optimal observer in the GRT model, and the vertical green lines are the individual criterion of participants. The red line is the SvM model extracted from the GRT model. Finally, the lighter red bands represent the 95 percent confidence interval. In the following paragraphs, I present and discuss the results of metacognitive sensitivity of TOT and FOK separately.

Metacognitive Sensitivity of TOT

By accounting for 97.49% of the behavioral data, the estimated GRT model provided a good fit to the data (see Fig. 6a). Figure 6b depicts the SvM curve representing metacognitive sensitivity of TOT. Based on this SvM curve, the sensitivity in the memory recognition task is dependent on the strength of TOT experiences. That is, the sensitivity in the memory recognition task is highest when participants are experiencing a high level of TOT. Accordingly, as the strength of TOT experiences decreases, so does the memory recognition sensitivity. Furthermore, the sensitivity of the memory recognition approaches zero (i.e., chance-level) in the area of low likelihood of metacognition. This indicates the survival of memory recognition processes in the absence of a TOT experience.

In addition, the SvM analysis indicates that participants adopted a conservative metacognitive criterion in comparison to the objective criterion. This means that participants are less likely to report experiencing a TOT even when they likely to be experiencing a metacognitive experience equivalent to a weak TOT state. That is, participants reported experiencing a TOT only if the experience was strong and profound.

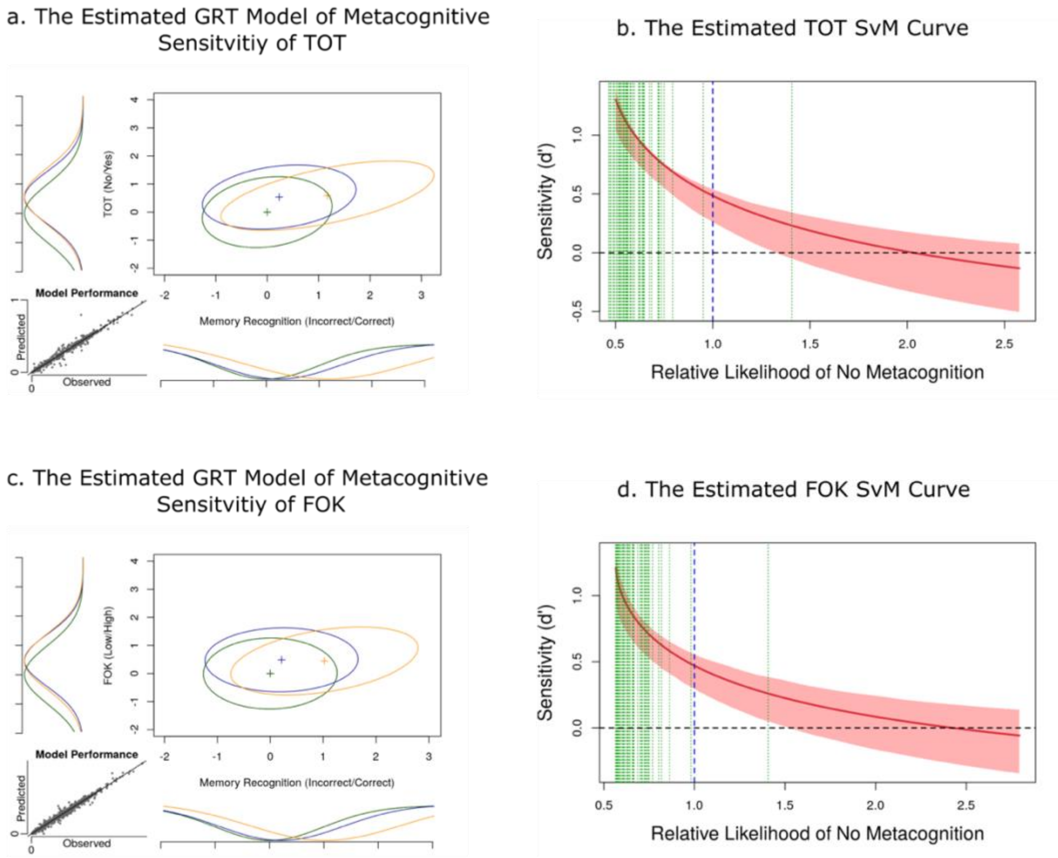

Fig. 6 The Results of GRT-based Analysis of Metacognitive Sensitivity of TOT and FOK in Experiment 2**.** The estimated GRT models of metacognitive sensitivity of TOT and FOK are shown in figure 6a and 6c respectively. In both GRT models, the yellow oval represents bidimensional probability distribution of correct recognition condition, the blue oval represents bidimensional probability distribution of incorrect recognition condition, and the green oval represents bidimensional probability distribution of catch trials. Moreover, the estimated SvM curve representing metacognitive sensitivity of TOT and FOK are shown in figure 6b and 6d respectively. In both SvM curves, the x-axis represents the relative likelihood of no metacognition, with zero representing the strongest level of a metacognitive experience. The y-axis represents sensitivity in the memory recognition task, with zero representing the chance-level. The vertical blue line is the objective criterion based on the optimal observer in the GRT model and the vertical green lines are the individual criterion of participants. The red line is the SvM model extracted from the GRT model, and the lighter red bands represent the 95 percent confidence interval.

Metacognitive Sensitivity of FOK

By accounting for 97.8% of the behavioral data, the estimated GRT model provided a good fit to the data (see Fig. 6c). Figure 6d depicts the SvM curve representing metacognitive sensitivity of FOK. Based on this SvM curve, the sensitivity in the memory recognition task is dependent on the strength of FOK experiences. That is, the sensitivity in the memory recognition task is highest when participants are experiencing a high level of FOK. Accordingly, as the strength of FOK experiences decreases, so does the memory recognition sensitivity. Furthermore, the sensitivity of the memory recognition approaches zero (i.e., chance-level) in the area of low likelihood of metacognition. This indicates the survival of memory recognition processes when participants were experiencing a low level of FOK.

In addition, the SvM analysis indicates that participants adopted a conservative metacognitive criterion in comparison to the objective criterion. This means that participants are less likely to report experiencing a high level of FOK. That is, participants reported experiencing a high level of FOK only if their FOK experience was strong.

Evaluating the Metacognitive Sensitivity of TOT and FOK Using Gamma Correlation

Metacognitive Sensitivity of TOT

Accuracy of performance in a memory recognition task was moderately correlated with TOT (γ=0.231, *standard error*= 0.021, *95% CI*=0.19 to 0.272), which was significantly higher than chance-level (Z=10.895, p<0.001). This indicates that experiencing a TOT is associated with a higher likelihood of correct recognition performance. This is in line with the results of GRT-based analysis of metacognitive sensitivity of TOT.

Metacognitive Sensitivity of FOK

Accuracy of performance in a memory recognition task was moderately correlated with FOK (γ=0.205, *standard error*= 0.019, *95% CI*=0.167 to 0.243), which was significantly higher than chance-level (Z=10.54, p<0.001). This indicates that experiencing a high FOK is associated with a higher likelihood of correct recognition performance. This is in line with the results of GRT-based analysis of metacognitive sensitivity of FOK.

GRT-Based Analysis of Influence of TOT and FOK on Metacognitive Sensitivity of Confidence

I presented the main results of this section in Figure 7. The figures in the left column (7a and 7c) depict the estimated meta-GRT models for each metacognitive judgment (TOT and FOK), and the figures in the right column (7b and 7d) depict meta-SvM curves extracted from each model. In all of the meta-SvM curve graphs, the x-axis represents the relative likelihood of no metacognition, with zero representing the strongest level of a metacognitive experience. The y-axis represents metacognitive sensitivity of confidence ratings, with zero representing the chance-level. The vertical blue line is the objective criterion based on the optimal observer in the meta-GRT model, and the vertical green lines are the individual criterion of participants. The red line is the meta-SvM model extracted from the meta-GRT model. Finally, the lighter red bands represent the 95 percent confidence interval.

The Influence of TOT on Metacognitive Sensitivity of Confidence

By accounting for 98.4% of the behavioral data, the estimated meta-GRT model provided a good fit to the data (see Fig. 7a). Figure 7b depicts the meta-SvM curve representing metacognitive sensitivity of confidence as a function of strength of TOT. Based on this meta-SvM curve, the metacognitive sensitivity of confidence is dependent on the strength of TOT experiences. That is, the metacognitive sensitivity of confidence is highest when participants are experiencing a high level of TOT. Accordingly, as the strength of TOT experiences decreases, so does the metacognitive sensitivity of confidence. Furthermore, the metacognitive sensitivity of confidence approaches zero (i.e., chance-level) in the area of low likelihood of metacognition. This indicates the survival of confidence-related processes in the absence of a TOT experience.

Similar to the results of GRT-based analysis of TOT, the meta-SvM analysis indicates that participants adopted a conservative metacognitive (TOT) criterion in comparison to the objective criterion. This means that participants are less likely to report experiencing a TOT even when they likely to be experiencing a metacognitive experience equivalent to a weak TOT state. That is, participants reported experiencing a TOT only if the experience was strong and profound.

The Influence of FOK on Metacognitive Sensitivity of Confidence

By accounting for 98.41% of the behavioral data, the estimated meta-GRT model provided a good fit to the data (see Fig. 7c). Figure 7d depicts the meta-SvM curve representing metacognitive sensitivity of confidence as a function of strength of FOK. Based on this meta-SvM curve, the metacognitive sensitivity of confidence is dependent on the strength of FOK experiences. That is, the metacognitive sensitivity of confidence is highest when participants are experiencing a high level of FOK. Accordingly, as the strength of FOK experiences decreases, so does the metacognitive sensitivity of confidence. Furthermore, the metacognitive sensitivity of confidence approaches zero (i.e., chance-level) in the area of low likelihood of metacognition. This indicates the survival of confidence-related processes when participants were experiencing a low level of FOK.

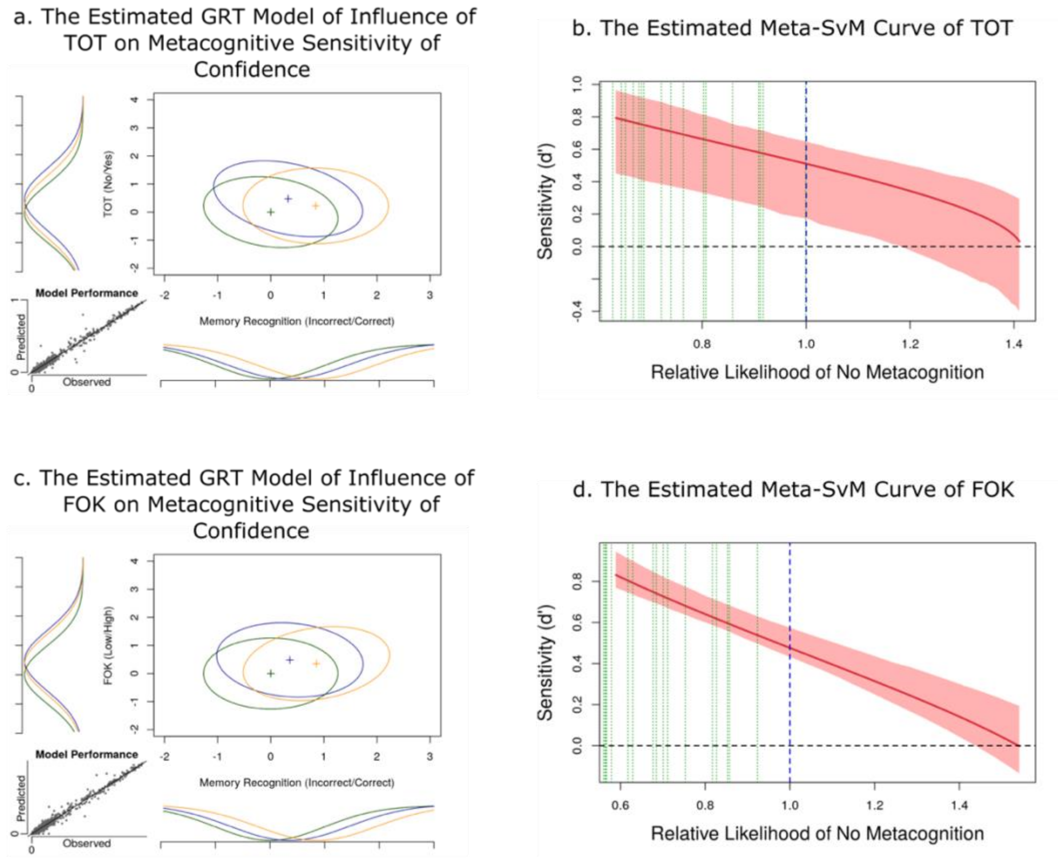

Fig. 7 The Results of GRT-based Analysis of Influence of TOT and FOK on Metacognitive Sensitivity of Confidence in Experiment 2**.** The estimated meta-GRT models are shown in figure 7a and 7c respectively. In both meta-GRT models, the yellow oval represents bidimensional probability distribution of correct recognition condition, the blue oval represents bidimensional probability distribution of incorrect recognition condition, and the green oval represents bidimensional probability distribution of catch trials. Moreover, the estimated meta-SvM curve representing metacognitive sensitivity of TOT and FOK are shown in figure 7b and 7d respectively. In both meta-SvM curves, the x-axis represents the relative likelihood of no metacognition, with zero representing the strongest level of a metacognitive experience. The y-axis represents metacognitive sensitivity of confidence ratings, with zero representing the chance-level. The vertical blue line is the objective criterion based on the optimal observer in the meta-GRT model and the vertical green lines are the individual criterion of participants. The red line is the meta-SvM model extracted from the meta-GRT model, and the lighter red bands represent the 95 percent confidence interval.

Similar to the results of GRT-based analysis of FOK, the meta-SvM analysis indicates that participants adopted a conservative metacognitive (FOK) criterion in comparison to the objective criterion. This means that participants are less likely to report experiencing a high level of FOK. That is, participants reported experiencing a high level of FOK only if their FOK experience was strong.

Evaluating the Influence of TOT and FOK on Average Confidence Rating

Evaluating the impact of TOT on average confidence rating showed that participants' confidence rating was significantly higher in the trials that they reported experiencing a TOT (M=2.90, SD=0.523) than the trials that they reported not experiencing a TOT (M=1.76, SD=0.509, χ^2 (1)= 47.1, p<0.001). Evaluating the impact of FOK on average confidence rating showed that participants' confidence rating was significantly higher in the trials that they reported experiencing a high FOK (M=2.88, SD=0.454) than the trials that they reported experiencing a low FOK (M=1.66, SD=0.412, χ^2 (1)= 51, p<0.001). Hence, experiencing a TOT or a high FOK associates with higher level of confidence.

Discussion

The purpose of Experiment 2 was to evaluate the metacognitive sensitivity of TOT and FOK and to evaluate the influence of TOT and FOK judgments on the metacognitive sensitivity of post-performance confidence using general-knowledge questions as cues. The results of the GRT-based analyses showed that experiencing TOT and a high FOK are associated with increase in sensitivity in the memory recognition task. That is, the highest level of recognition sensitivity was observed in the area of high likelihood of metacognition and when participants were experiencing the highest level of each metacognitive experience. Gamma correlation analysis also supported these results.

Moreover, the results of the GRT-based analyses showed that experiencing TOT and a high FOK are associated with increase in metacognitive sensitivity of confidence judgments. That is, the highest level of metacognitive sensitivity of confidence was observed in the area of high likelihood of metacognition and when participants were experiencing the highest level of TOT or FOK. The results also indicate that experience of TOT or a high FOK is also associated with higher confidence ratings. Finally, comparing participants' metacognitive bias against the objective criterion showed that participants adopted a conservative metacognitive bias in reporting experiencing a TOT and high FOK. That is, they were less likely to report experiencing a TOT or a high FOK.

IV. General Conclusion

Even though research has provided extensive support for metacognitive sensitivity of different metacognitive judgments, the accuracy of the measures used to estimate metacognitive sensitivity of different metacognitive judgments have been criticized (e.g., see Fleming & Lau, 2014; Shekhar & Rahnev, 2021a). That is, previous measures of metacognitive sensitivity fail to separate the impact of different factors that may influence participants' metacognitive reports, and therefore, such factors may influence estimated metacognitive sensitivities resulted from these measures. Moreover, it is not clear if confidence judgments more accurately predict performance of the memory recognition task when participants experience a TOT or a high level of FOK. This last question addresses the issue of whether there are common mechanisms across both prospective and retrospective metamemory.

For this reason, my first goal was to provide a complementary measure of metacognitive sensitivity that can be used to provide a bias-free estimation of metacognitive sensitivity, especially when the research questions require a fine measure of such sensitivity. To this end, I evaluated metacognitive sensitivity of TOT and FOK using GRT-based analyses. Below I discuss the results of the application of this model-based analysis on each of these metacognitive judgments separately.

The results of this model-based analysis indicated that experiencing a TOT state is associated with increase in the possibility of correct recognition of missing information. That is, the results of both experiments indicated that experience of TOT is associated with increase in sensitivity of participants in the memory recognition task. The TOT results are in line with the previous research on metacognitive sensitivity of TOT using other measures of metacognitive sensitivity (e.g., Bloom et al., 2018; A. Brown, 1991; Schwartz, 2001, 2010). For example, Schwartz (2010) showed that experiencing a TOT for general-knowledge questions and word definitions correlates with performance in a memory recognition task. This was evident by higher than chance gamma correlation between TOTs and recognition as well as higher correct recognition percentage in the trials that participants reported experiencing a TOT than the trials that they did not report experiencing a TOT. Thus, with regard to sensitivity, I replicate the long-standing finding that TOTs predict performance. However, no research until this project has yet addressed a bias-free assessment of metacognitive sensitivity of TOTs.

This analysis showed that participants tend to adopt a conservative metacognitive bias and report experiencing a TOT less frequently than an optimal metacognitive observer. This means that compared to an optimal metacognitive observer, participants are less likely to report experiencing a TOT. That is, participants may report a TOT only when their metacognitive experience is profound and strong. To the best of my knowledge, this is the first report of conservative metacognitive bias in regards to TOT, and I suspect that many other researchers will find it both novel and surprising.

In addition, this GRT-based analysis showed that a high FOK is also associated with increase in the possibility of correct recognition of missing information. That is, across both experiments, a high FOK was associated with increase in sensitivity of participants in the memory recognition task. This is in line with the previous research on metacognitive sensitivity of FOK using other measures of metacognitive sensitivity (e.g., Hertzog et al., 2010; Metcalfe et al., 1993; Sacher et al., 2009; Schwartz et al., 2014). For example, Nelson et al. (1982) showed that participants performed better in memory recognition task, for the items that they ranked as more likely to be recognized (FOK task), and Hertzog et al. (2010) showed that FOK is associated with better recognition performance in both younger and older adults. Hence, I replicate the long-standing finding that FOK judgments predict performance. Similar to the TOT results, however, no research until this project has yet addressed a bias-free assessment of metacognitive sensitivity of FOK.

Similar to the TOT results, participants also adopted a conservative bias to report their FOK experiences. This means that compared to an optimal metacognitive observer, participants were less likely to report having a high FOK experience, and reporting a high FOK experience required a strong and profound FOK experience. To the best of my knowledge, this is also the first report of conservative metacognitive bias in regards to FOK, and I suspect that many other researchers will find it both novel and surprising.

In both analyses of metacognitive sensitivity of TOT and FOK, I also observed above chance-level recognition sensitivity in the area of low likelihood of metacognition or in the absence of TOT or when participants were experiencing a low FOK. Thus, even when recall fails and no metacognitive experience occurs, recognition performance may still be above chance. However, recognition reaches even higher sensitivity when the metacognition occurs. This may imply that TOT and FOK may have a top-down influence on already active memory processes and may amplify these weak but still significant processes (also see Bloom et al., 2018; Cleary et al., 2021; Mitchum et al., 2016). In this way, TOTs and FOK might alter the processes of retrieval, leading to a better recognition performance (also see Cleary et al., 2021).

That TOTs and FOKs are predictive of performance, but conservative in bias is compatible with the current theories of TOT such as the direct access theories (R. Brown & McNeill, 1966; Gollan & Brown, 2006) and the heuristic–metacognitive theories of TOT (Schwartz, 2006; Schwartz & Metcalfe, 2011), as well as the theories of FOK such as the accessibility hypothesis (Koriat, 1993, 1995) and the cue-familiarity hypothesis of FOK (Brewer et al., 2010; Metcalfe et al., 1993). That is, either direct or heuristic accounts of judgments can be accommodate the conservative bias found here. Thus, these results do not provide evidence in favor of a specific theory of TOTs or FOK judgments.

As I mentioned before, I was also interested in evaluating the influence of TOTs and FOKs on the metacognitive sensitivity of confidence judgments. That is, I was interested in determining whether experiencing a TOT or a high FOK may be associated with increase in the metacognitive of metacognitive sensitivity of confidence judgments. To this end, I utilized the new GRT-based analysis. The results showed that experiencing a TOT state is associated with increase in the metacognitive sensitivity of confidence. That is, the results of both experiments indicated that confidence judgments were more indicative of memory recognition performance when participants were experiencing a TOT. The results showed that experiencing a high FOK is also associated with increase in the metacognitive sensitivity of confidence. That is, the results of both experiments indicated that confidence judgments were more indicative of memory recognition performance when participants were experiencing a high FOK. To the best of my knowledge, this is the first report of influence of TOT and FOK on metacognitive sensitivity of confidence judgments.

In addition, behavioral report of TOT or a high FOK enhances the probability of reporting a high confidence. That is, participant reported higher level of confidence in the trials that they also reported experiencing a TOT or a high FOK. These results indicate that there is an association between behavioral report of high level of different metacognitive judgments such as FOK, TOT and confidence.

The results of the meta-SvM analyses as well as the results indicating influence of report of TOT and FOK on the level of confidence, I argue, are in line with a hierarchical conceptualization of metacognition (Arango-Muñoz, 2011). According to this conceptualization, metacognitive system is composed of two different levels: the low-level metacognition that is composed of fast, automatic, and nonconscious metacognitive processes and the high-level metacognition that is composed of slow and conscious metacognitive experiences. Arango-Muñoz (2011) classified TOT experiences as a low-level and confidence judgments as high-level metacognition. I disagree with this classification based on two arguments: TOTs are often classified as conscious metacognitive experiences (Schwartz & Pournaghdali, 2016). Hence, TOT meet the requirement of being a high-level metacognitive experience. Confidence judgments, on the other hand, are not necessarily conscious experiences and can operate in the absence of consciousness[28] (see Jachs et al., 2015; Pournaghdali et al., in revision). Therefore, I classify TOTs and FOKs as high-level metacognitive experiences and confidence as a low-level metacognitive experience.

---

[28] However, one can argue that there are two modes of confidence: high-level confidence judgments that are conscious by nature and low-level confidence judgments that operate in the absence of consciousness.

Based on this, I argue that TOT and FOK impact the metacognitive sensitivity of confidence based on four possibilities: first, it is possible that experience of TOT and FOK may have a top-down influence on memory processes. Hence, by enhancing the quality of the object-level information available to confidence system and making such information more salient, TOT and FOK may enhance confidence related processes. Second, it is possible that TOT and FOK have a direct top-down influence on confidence itself regardless of their top-down influence on object-level memory processes. That is, the enhancement of metacognitive sensitivity might be the result of direct top-down effect of TOT and FOK on confidence-related processes. Based on this possibility, experience of TOT and FOK may improve efficiency of confidence-related process in evaluating object-level information. This, therefore, manifests itself as an enhanced metacognitive sensitivity of confidence as well as a higher confidence rating when participants experience a TOT or a high FOK. Third, it is possible that there are two modes of confidence experiences: a low-level confidence that provides a coarse evaluation of object-level processes and a high-level confidence that provides a finer evaluation of object-level processes. Based on this, it is possible that TOT and FOK trigger the high-level confidence processes, and in this way, enhance the metacognitive sensitivity of confidence. Finally, it is also possible that a common metacognitive mechanism exists. In this case, TOT, FOK and confidence are different elements of this metacognitive system. Accordingly, enhancement of a general metacognitive evaluation of object-level processes may manifest itself as simultaneous enhancement of metacognitive sensitivity of TOT, FOK and confidence. However, the above chance-level metacognitive sensitivity of confidence rating in the area of low likelihood of metacognition of TOT and FOK argue against this possibility. If there was only one metacognitive system with different element, then we would expect chance-level metacognitive sensitivity of confidence in the absence of TOT and FOK judgments. In conclusion, I argue that future research on metacognition should evaluate all of these possibilities.

As I mentioned in the previous paragraphs, participants adopted a conservative metacognitive bias to report experiencing a TOT and high FOK. This pattern is consistent across both experiments and across the four GRT-based analyses. This is an interesting finding that needs more considerations in future, but I will speculate here. I suspect that participants adopted a conservative metacognitive bias in reporting experiencing a TOT and high FOK because of the graded nature of these two experiences, as well participants' inefficiency in distinguishing different levels of these two experiences. For example, I argue that TOT is not a binary experience with two levels (TOT and no TOT), but a graded experience with different subjective levels. Hence, there are likely different magnitudes of TOT experiences between no TOT and full-strength TOT. That is, participants may experience different levels of TOT such as a very weak TOT, a moderate TOT, and a very strong TOT. Moreover, research shows that participants may not be particularly good at introspection and at generating an accurate report of such introspection (see Sandberg et al., 2010). Based on this, when participants are experiencing a weaker magnitude TOT, they may not be able to distinguish it from not experiencing a TOT at all. Thus, they adopt a conservative criterion to report their experience of TOT. Note that the same explanation is also applicable to the conservative metacognitive bias in regards to FOK. Therefore, participants adopt a conservative metacognitive bias, when reporting a TOT or a high FOK, because of their inability to distinguish a weak metacognitive experience (TOT or FOK) from the lack of such experience (also see Schwartz et al., 2000).

Based on this, future research ought to investigate this and other possible explanations for the conservative metacognitive bias in regard to both TOT and FOK. More specifically, future research should investigate the reason(s) and mechanism(s) of this effect in regard to both TOT and FOK. In addition, whether conservative bias is a fundamental quality of metacognitive system and the conditions in which participants may adopt a more optimal or liberal metacognitive criterion should be investigated in future. I think that this model-based approach provides future research with an opportunity to investigate these important questions.

Moving to measurement issues, I argue that this GRT-based analysis has advantages that make it an important tool for evaluating metacognitive sensitivity. First, the estimation of sensitivity in an SvM curve is independent of bias. That is, participants' metacognitive bias, has no influence on their metacognitive sensitivity. This will allow us to evaluate metacognitive sensitivity of different metacognitive judgments more accurately. Second, in addition to representing conditional sensitivity, an SvM curve also depicts participants' individual metacognitive biases as well as an objective criterion based on an optimal metacognitive observer. Hence, we can assess participants' metacognitive criterion in reference to the optimal criterion and learn more about their metacognitive responses. This feature of SvM analysis provides us with an outstanding opportunity to study conditions that may impact participants' metacognitive calibration, such as subjective inflation in peripheral vision, which is defines as metacognitive overconfidence about qualities of perception in the visual periphery (e.g., Knotts et al., 2019; Odegaard et al., 2018). Therefore, this model-based analysis will provide us with an opportunity to investigate the reason(s) and mechanism(s) of conservative or liberal metacognitive bias of different metacognitive judgments including TOTs and FOKs.

Third, SvM analysis is compatible with different scales of a metacognitive task. That is, we can use different scales (e.g., binary, 4-point scale or 100-point scale) to measure a metacognitive experience and SvM curve is compatible with these different scales. However, using a scale that has more than 2 categories requires more parameters to estimate which may require longer computations, larger sample size and more accurate selection of a GRT model[29]. Finally, SvM analysis evaluates any metacognitive experience as a continuous phenomenon even when we use a task with a categorical scale (such as binary) to assess a metacognitive experience (c.f., Nelson, 1984). Note that regardless of the scale that we use to assess a metacognitive experience, SvM analysis of metacognition provide us with a bias-free evaluation of metacognitive bias.

Although these results are first bias-free indication of metacognitive sensitivity of metamemory judgments, and the first indication of influence of TOT and FOK on metacognitive sensitivity of confidence, they are limited only to semantic-memory paradigm and to only the three metacognitive judgments that I evaluated in this study. However, advantages of SvM curve analysis in evaluating metacognitive sensitivity and metacognitive bias will allow us to test different critical questions regarding different metacognitive experiences.

---

[29] Traditional GRT model is prone to overfitting when number of to-be-estimated parameters increases, but GRT-wIND resolves the overfitting problem of GRT by providing more degrees of freedom (see Soto et al., 2015).

First, I think that this GRT-based analysis can be used to evaluate metacognitive sensitivity of different metacognitive judgments in regards to different memory, cognitive, and perceptual tasks. For example, we can use this GRT-based approach to study metacognitive sensitivity of JOLs. More specifically, research show that introducing a delay between studying an item and making a JOL judgment improves metacognitive sensitivity of JOLs. Based on this, we can study such effects using this model-based approach with more accuracy. Moreover, we can use this approach to evaluate conditions that may change participants' metacognitive sensitivity or metacognitive bias. For example, we can use this GRT-based analysis approach to investigate the possibility of impairment of metacognitive sensitivity or metacognitive bias of different metacognitive judgments in different psychological and neurological conditions such as Alzheimer's (Cosentino et al., 2007; Garcia-Cordero et al., 2021; Pappas et al., 1992), Schizophrenia (e.g., Bacon et al., 2018; Lysaker et al., 2011; Rouy et al., 2021) and blindsight (Ko & Lau, 2012). We can also use this model-based approach to study interesting questions in educational research, such as whether we can enhance students' metacognitive calibration when they must judge the level of their knowledge in a specific subject (for example, see Alexander, 2013).

Moreover, we can implement this approach to evaluate the neurocognitive bases of different metacognitive judgments. Implementing this approach will allow us to identify the neurocognitive mechanism(s) that may underlie the metacognitive sensitivity and neurocognitive mechanism(s) that may underlie the metacognitive bias of a metacognitive judgment (e.g., TOT or FOK). This, in turn, will be an initial step in the path toward understanding the neural mechanism(s) that create different metacognitive judgments.

Accordingly, utilizing this approach will allow us to investigate the possibility of a general neurocognitive mechanism(s) that may induce different metacognitive judgments. Finally, this model-based analysis can be used to evaluate the interaction between different metacognitive judgments (JOL, FOK, EOL, etc.). That is, we can use this model-based analysis to evaluate neurocognitive mechanism(s) of different metacognitive judgments as well as possible interaction between such mechanisms.

References

Alexander, P. A. (2013). Calibration: What is it and why it matters? An introduction to the special issue on calibrating calibration. *Learning and Instruction*, *24*, 1–3. https://doi.org/10.1016/j.learninstruc.2012.10.003

Allen, M., Glen, J. C., Müllensiefen, D., Schwarzkopf, D. S., Fardo, F., Frank, D., Callaghan, M. F., & Rees, G. (2017). Metacognitive ability correlates with hippocampal and prefrontal microstructure. *NeuroImage*, *149*, 415–423. https://doi.org/10.1016/j.neuroimage.2017.02.008

Arango-Muñoz, S. (2011). Two Levels of Metacognition. *Philosophia*, *39*(1), 71–82. https://doi.org/10.1007/s11406-010-9279-0

Ariel, R., Dunlosky, J., & Bailey, H. (2009). Agenda-based regulation of study-time allocation: When agendas override item-based monitoring. *Journal of Experimental Psychology. General*, *138*(3), 432–447. https://doi.org/10.1037/a0015928

Ashby, F. G., & Soto, F. A. (2015). Multidimensional signal detection theory. In *The Oxford handbook of computational and mathematical psychology* (pp. 13–34). Oxford University Press.

Bacon, E., Pillot, M., Izaute, M., & Schwartz, B. L. (2018). The basis of feeling-of-knowing judgments in patients with schizophrenia. *Metacognition and Learning*, *13*(1), 91–108. https://doi.org/10.1007/s11409-018-9179-4

Baird, B., Cieslak, M., Smallwood, J., Grafton, S. T., & Schooler, J. W. (2015). Regional white matter variation associated with domain-specific metacognitive accuracy. *Journal of Cognitive Neuroscience*, *27*(3), 440–452. https://doi.org/10.1162/jocn_a_00741

Baird, B., Smallwood, J., Gorgolewski, K. J., & Margulies, D. S. (2013). Medial and lateral networks in anterior prefrontal cortex support metacognitive ability for memory and perception. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *33*(42), 16657–16665. https://doi.org/10.1523/JNEUROSCI.0786-13.2013

Baizer, J. S., Ungerleider, L. G., & Desimone, R. (1991). Organization of visual inputs to the inferior temporal and posterior parietal cortex in macaques. *The Journal of Neuroscience*, *11*(1), 168–190.

Baroni, F., van Kempen, J., Kawasaki, H., Kovach, C. K., Oya, H., Howard, M. A., Adolphs, R., & Tsuchiya, N. (2017). Intracranial markers of conscious face perception in humans. *NeuroImage*, *162*, 322–343. https://doi.org/10.1016/j.neuroimage.2017.08.074

Barrett, A. B., Dienes, Z., & Seth, A. K. (2013). Measures of metacognition on signal-detection theoretic models. *Psychological Methods*, *18*(4), 535–552. https://doi.org/10.1037/a0033268

Benjamin, A. S., Bjork, R. A., & Schwartz, B. L. (1998). The mismeasure of memory: When retrieval fluency is misleading as a metamnemonic index. *Journal of Experimental Psychology. General*, *127*(1), 55–68. https://doi.org/10.1037//0096-3445.127.1.55

Benjamin, A. S., & Diaz, M. (2008). Measurement of relative metamnemonic accuracy. In *Handbook of metamemory and memory* (pp. 73–94). Psychology Press.

Bjork, R. A., Dunlosky, J., & Kornell, N. (2013). Self-regulated learning: Beliefs, techniques, and illusions. *Annual Review of Psychology*, *64*, 417–444. https://doi.org/10.1146/annurev-psych-113011-143823

Bloom, P. A., Friedman, D., Xu, J., Vuorre, M., & Metcalfe, J. (2018). Tip-of-the-tongue states predict enhanced feedback processing and subsequent memory. *Consciousness and Cognition*, *63*, 206–217. https://doi.org/10.1016/j.concog.2018.05.010

Brewer, G. A., Marsh, R. L., Clark-Foos, A., & Meeks, J. T. (2010). Noncriterial recollection influences metacognitive monitoring and control processes. *The Quarterly Journal of Experimental Psychology*, *63*(10), 1936–1942. https://doi.org/10.1080/17470210903551638

Brown, A. (1991). A review of the tip-of-the-tongue experience. *Psychological Bulletin*, *109*(2), 204–223. https://doi.org/10.1037/0033-2909.109.2.204

Brown, R., & McNeill, D. (1966). The "tip of the tongue" phenomenon. *Journal of Verbal Learning & Verbal Behavior*, *5*(4), 325–337. https://doi.org/10.1016/S0022-5371(66)80040-3

Capobianco, L., Faija, C., Husain, Z., & Wells, A. (2020). Metacognitive beliefs and their relationship with anxiety and depression in physical illnesses: A systematic review. *PloS One*, *15*(9), e0238457. https://doi.org/10.1371/journal.pone.0238457

Chalmers, D. J. (1995). Facing Up to the Problem of Consciousness. *Journal of Consciousness Studies*, *2*(3), 200–219.

Chalmers, D. J. (2013). How can we construct a science of consciousness? *Annals of the New York Academy of Sciences*, *1303*, 25–35. https://doi.org/10.1111/nyas.12166

Chua, E. F., Hannula, D. E., & Ranganath, C. (2012). Distinguishing highly confident accurate and inaccurate memory: Insights about relevant and irrelevant influences on memory confidence. *Memory (Hove, England)*, *20*(1), 48–62. https://doi.org/10.1080/09658211.2011.633919

Cleary, A. M. (2006). Relating familiarity-based recognition and the tip-of-the-tongue phenomenon: Detecting a word's recency in the absence of access to the word. *Memory & Cognition*, *34*(4), 804–816. https://doi.org/10.3758/BF03193428

Cleary, A. M. (2019). The biasing nature of the tip-of-the-tongue experience: When decisions bask in the glow of the tip-of-the-tongue state. *Journal of Experimental Psychology: General*, *148*(7), 1178–1191. https://doi.org/10.1037/xge0000520

Cleary, A. M., & Claxton, A. B. (2015). The tip-of-the-tongue heuristic: How tip-of-the-tongue states confer perceptibility on inaccessible words. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *41*(5), 1533–1539. https://doi.org/10.1037/xlm0000097

Cleary, A. M., Konkel, K. E., Nomi, J. S., & McCabe, D. P. (2010). Odor recognition without identification. *Memory & Cognition*, *38*(4), 452–460. https://doi.org/10.3758/MC.38.4.452

Cleary, A. M., McNeely-White, K. L., Russell, S. A., Huebert, A. M., & Hausman, H. (2021). The tip-of-the-tongue state as a form of access to information: Use of tip-of-the-tongue states for strategic adaptive test-taking. *Journal of Applied Research in Memory and Cognition*, *10*(1), 131–142. https://doi.org/10.1016/j.jarmac.2020.08.013

Cleary, A. M., & Reyes, N. L. (2009). Scene recognition without identification. *Acta Psychologica*, *131*(1), 53–62. https://doi.org/10.1016/j.actpsy.2009.02.006

Cosentino, S., Metcalfe, J., Butterfield, B., & Stern, Y. (2007). Objective metamemory testing captures awareness of deficit in Alzheimer's disease. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, *43*(7), 1004–1019. https://doi.org/10.1016/s0010-9452(08)70697-x

D'Angelo, M. C., & Humphreys, K. R. (2012). Emotional cues do not increase the likelihood of tip-of-the-tongue states. *Memory & Cognition*, *40*(8), 1331–1338. https://doi.org/10.3758/s13421-012-0235-z

D'Angelo, M. C., & Humphreys, K. R. (2015). Tip-of-the-tongue states reoccur because of implicit learning, but resolving them helps. *Cognition*, *142,* 166–190. https://doi.org/10.1016/j.cognition.2015.05.019

Dennett, D. C. (2018). Facing up to the hard question of consciousness. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *373*(1755), 20170342. https://doi.org/10.1098/rstb.2017.0342

Elman, J. A., Klostermann, E. C., Marian, D. E., Verstaen, A., & Shimamura, A. P. (2012). Neural correlates of metacognitive monitoring during episodic and semantic retrieval. *Cognitive, Affective & Behavioral Neuroscience*, *12*(3), 599–609. https://doi.org/10.3758/s13415-012-0096-8

Evans, S., & Azzopardi, P. (2007). Evaluation of a “bias-free” measure of awareness. *Spatial Vision*, *20*(1–2), 61–77.

Faivre, N., Filevich, E., Solovey, G., Kühn, S., & Blanke, O. (2018). Behavioral, Modeling, and Electrophysiological Evidence for Supramodality in Human Metacognition. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *38*(2), 263–277. https://doi.org/10.1523/JNEUROSCI.0322-17.2017

Fleck, M. S., Daselaar, S. M., Dobbins, I. G., & Cabeza, R. (2006). Role of prefrontal and anterior cingulate regions in decision-making processes shared by memory and nonmemory tasks. *Cerebral Cortex (New York, N.Y.: 1991)*, *16*(11), 1623–1630. https://doi.org/10.1093/cercor/bhj097

Fleming, S. M., Huijgen, J., & Dolan, R. J. (2012). Prefrontal contributions to metacognition in perceptual decision making. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *32*(18), 6117–6125. https://doi.org/10.1523/JNEUROSCI.6489-11.2012

Fleming, S. M., & Lau, H. (2014). How to measure metacognition. *Frontiers in Human Neuroscience*, *8*. https://doi.org/10.3389/fnhum.2014.00443

Fleming, S. M., Massoni, S., Gajdos, T., & Vergnaud, J.-C. (2016). Metacognition about the past and future: Quantifying common and distinct influences on prospective and retrospective judgments of self-performance. *Neuroscience of Consciousness*, *2016*(1). https://doi.org/10.1093/nc/niw018

Fleming, S. M., Ryu, J., Golfinos, J. G., & Blackmon, K. E. (2014). Domain-specific impairment in metacognitive accuracy following anterior prefrontal lesions. *Brain: A Journal of Neurology*, *137*(Pt 10), 2811–2822. https://doi.org/10.1093/brain/awu221

Fleming, S. M., Weil, R. S., Nagy, Z., Dolan, R. J., & Rees, G. (2010). Relating introspective accuracy to individual differences in brain structure. *Science (New York, N.Y.)*, *329*(5998), 1541–1543. https://doi.org/10.1126/science.1191883

Galvin, S. J., Podd, J. V., Drga, V., & Whitmore, J. (2003). Type 2 tasks in the theory of signal detectability: Discrimination between correct and incorrect decisions. *Psychonomic Bulletin & Review*, *10*(4), 843–876.

Garcia-Cordero, I., Migeot, J., Fittipaldi, S., Aquino, A., Campo, C. G., García, A., & Ibáñez, A. (2021). Metacognition of emotion recognition across neurodegenerative diseases. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, *137*, 93–107. https://doi.org/10.1016/j.cortex.2020.12.023

Gawrylowicz, J., Memon, A., Scoboria, A., Hope, L., & Gabbert, F. (2014). Enhancing older adults’ eyewitness memory for present and future events with the Self-

Administered Interview. *Psychology and Aging*, *29*(4), 885–890. https://doi.org/10.1037/a0038048

Gollan, T. H., & Brown, A. (2006). From tip-of-the-tongue (TOT) data to theoretical implications in two steps: When more TOTs means better retrieval. *Journal of Experimental Psychology. General*, *135*(3), 462–483. https://doi.org/10.1037/0096-3445.135.3.462

Green, D. M., & Swets, J. A. (1966). *Signal detection theory and psychophysics*. John Wiley.

Grimaldi, P., Lau, H., & Basso, M. A. (2015). There are things that we know that we know, and there are things that we do not know we do not know: Confidence in decision-making. *Neuroscience and Biobehavioral Reviews*, *55*, 88–97. https://doi.org/10.1016/j.neubiorev.2015.04.006

Hallam, B., Chan, J., Gonzalez Costafreda, S., Bhome, R., & Huntley, J. (2020). What are the neural correlates of meta-cognition and anosognosia in Alzheimer's disease? A systematic review. *Neurobiology of Aging*, *94*, 250–264. https://doi.org/10.1016/j.neurobiolaging.2020.06.011

Hanczakowski, M., Zawadzka, K., Collie, H., & Macken, B. (2017). Metamemory in a familiar place: The effects of environmental context on feeling of knowing. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *43*(1), 59–71. https://doi.org/10.1037/xlm0000292

Hanley, J. R., & Chapman, E. (2008). Partial knowledge in a tip-of-the-tongue state about two- and three-word proper names. *Psychonomic Bulletin & Review*, *15*(1), 156–160. https://doi.org/10.3758/pbr.15.1.156

Hart, J. T. (1965). Memory and the feeling-of-knowing experience. *Journal of Educational Psychology*, *56*(4), 208–216. https://doi.org/10.1037/h0022263

Henson, R. N., Rugg, M. D., Shallice, T., & Dolan, R. J. (2000). Confidence in recognition memory for words: Dissociating right prefrontal roles in episodic retrieval. *Journal of Cognitive Neuroscience*, *12*(6), 913–923. https://doi.org/10.1162/08989290051137468

Hertzog, C., Dunlosky, J., & Sinclair, S. M. (2010). Episodic Feeling-of-Knowing Resolution Derives from the Quality of Original Encoding. *Memory & Cognition*, *38*(6), 771–784. https://doi.org/10.3758/MC.38.6.771

Higham, P. A., Perfect, T. J., & Bruno, D. (2009). Investigating strength and frequency effects in recognition memory using type-2 signal detection theory. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *35*(1), 57–80. https://doi.org/10.1037/a0013865

Huijbers, W., Papp, K. V., LaPoint, M., Wigman, S. E., Dagley, A., Hedden, T., Rentz, D. M., Schultz, A. P., & Sperling, R. A. (2017). Age-Related Increases in Tip-of-the-tongue are Distinct from Decreases in Remembering Names: A Functional MRI Study. *Cerebral Cortex (New York, N.Y.: 1991)*, *27*(9), 4339–4349. https://doi.org/10.1093/cercor/bhw234

Jachs, B., Blanco, M. J., Grantham-Hill, S., & Soto, D. (2015). On the independence of visual awareness and metacognition: A signal detection theoretic analysis. *Journal of Experimental Psychology: Human Perception and Performance*, *41*(2), 269–276. https://doi.org/10.1037/xhp0000026

Jemstedt, A., Kubik, V., & Jönsson, F. U. (2017). What moderates the accuracy of ease of learning judgments? *Metacognition and Learning*, *12*(3), 337–355. https://doi.org/10.1007/s11409-017-9172-3

Jemstedt, A., Schwartz, B. L., & Jönsson, F. U. (2018). Ease-of-learning judgments are based on both processing fluency and beliefs. *Memory (Hove, England)*, *26*(6), 807–815. https://doi.org/10.1080/09658211.2017.1410849

Jiang, Y., Shannon, R. W., Vizueta, N., Bernat, E. M., Patrick, C. J., & He, S. (2009). Dynamics of processing invisible faces in the brain: Automatic neural encoding of facial expression information. *NeuroImage*, *44*(3), 1171–1177. https://doi.org/10.1016/j.neuroimage.2008.09.038

Kellij, S., Fahrenfort, J., Lau, H., Peters, M. A. K., & Odegaard, B. (2021). An investigation of how relative precision of target encoding influences metacognitive performance. *Attention, Perception & Psychophysics*, *83*(1), 512–524. https://doi.org/10.3758/s13414-020-02190-0

Kiani, R., Corthell, L., & Shadlen, M. N. (2014). Choice certainty is informed by both evidence and decision time. *Neuron*, *84*(6), 1329–1342. https://doi.org/10.1016/j.neuron.2014.12.015

Kikyo, H., & Miyashita, Y. (2004). Temporal lobe activations of "feeling-of-knowing" induced by face-name associations. *NeuroImage*, *23*(4), 1348–1357. https://doi.org/10.1016/j.neuroimage.2004.08.013

Kikyo, H., Ohki, K., & Miyashita, Y. (2002). Neural correlates for feeling-of-knowing: An fMRI parametric analysis. *Neuron*, *36*(1), 177–186. https://doi.org/10.1016/s0896-6273(02)00939-x

Knotts, J. D., Odegaard, B., & Lau, H. (2018). Neuroscience: The Key to Consciousness May Not Be under the Streetlight. *Current Biology: CB*, *28*(13), R749–R752. https://doi.org/10.1016/j.cub.2018.05.033

Knotts, J. D., Odegaard, B., Lau, H., & Rosenthal, D. (2019). Subjective inflation: Phenomenology's get-rich-quick scheme. *Current Opinion in Psychology*, *29*, 49–55. https://doi.org/10.1016/j.copsyc.2018.11.006

Ko, Y., & Lau, H. (2012). A detection theoretic explanation of blindsight suggests a link between conscious perception and metacognition. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *367*(1594), 1401–1411. https://doi.org/10.1098/rstb.2011.0380

Koriat, A. (1993). How do we know that we know? The accessibility model of the feeling of knowing. *Psychological Review*, *100*(4), 609–639. https://doi.org/10.1037/0033-295x.100.4.609

Koriat, A. (1995). Dissociating knowing and the feeling of knowing: Further evidence for the accessibility model. *Journal of Experimental Psychology: General*, *124*(3), 311–333. https://doi.org/10.1037/0096-3445.124.3.311

Koriat, A. (2000). The feeling of knowing: Some metatheoretical implications for consciousness and control. *Consciousness and Cognition*, *9*(2 Pt 1), 149–171. https://doi.org/10.1006/ccog.2000.0433

Koriat, A. (2007). Metacognition and consciousness. In P. D. Zelazo, M. Moscovitch, & E. Thompson (Eds.), *The Cambridge handbook of consciousness* (pp. 289–325). Cambridge University Press. https://doi.org/10.1017/CBO9780511816789.012

Koriat, A., & Levy-Sadot, R. (2001). The combined contributions of the cue-familiarity and accessibility heuristics to feelings of knowing. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *27*(1), 34–53. https://doi.org/10.1037/0278-7393.27.1.34

Koriat, A., & Lieblich, I. (1974). What does a person in a "TOT" state know that a person in a "don't know" state doesn't know? *Memory & Cognition*, *2*(4), 647–655. https://doi.org/10.3758/BF03198134

Kornell, N., Rhodes, M. G., Castel, A. D., & Tauber, S. K. (2011). The ease-of-processing heuristic and the stability bias: Dissociating memory, memory beliefs, and memory judgments. *Psychological Science*, *22*(6), 787–794. https://doi.org/10.1177/0956797611407929

Kunimoto, C., Miller, J., & Pashler, H. (2001). Confidence and accuracy of near-threshold discrimination responses. *Consciousness and Cognition*, *10*(3), 294–340. https://doi.org/10.1006/ccog.2000.0494

Lau, H. (2008). Are we studying consciousness yet? In *Frontiers of Consciousness: Chichele Lectures*. Oxford University Press.

Lau, H., & Passingham, R. E. (2006). Relative blindsight in normal observers and the neural correlate of visual consciousness. *Proceedings of the National Academy of Sciences of the United States of America*, *103*(49), 18763–18768. https://doi.org/10.1073/pnas.0607716103

Lau, H., & Rosenthal, D. (2011). Empirical support for higher-order theories of conscious awareness. *Trends in Cognitive Sciences*, *15*(8), 365–373. https://doi.org/10.1016/j.tics.2011.05.009

LeDoux, J. E., Michel, M., & Lau, H. (2020). A little history goes a long way toward understanding why we study consciousness the way we do today. *Proceedings of the National Academy of Sciences of the United States of America*, *117*(13), 6976–6984. https://doi.org/10.1073/pnas.1921623117

Lee, A. L. F., Ruby, E., Giles, N., & Lau, H. (2018). Cross-Domain Association in Metacognitive Efficiency Depends on First-Order Task Types. *Frontiers in Psychology*, *9*, 2464. https://doi.org/10.3389/fpsyg.2018.02464

Lysaker, P. H., Erickson, M. A., Buck, B., Buck, K. D., Olesek, K., Grant, M. L. A., Salvatore, G., Popolo, R., & Dimaggio, G. (2011). Metacognition and social function in schizophrenia: Associations over a period of five months. *Cognitive Neuropsychiatry*, *16*(3), 241–255. https://doi.org/10.1080/13546805.2010.530470

Macmillan, N. A., & Creelman, C. D. (2005). *Detection theory: A user's guide*. Erlbaum Inc.

Mamassian, P. (2016). Visual Confidence. *Annual Review of Vision Science*, *2*, 459–481. https://doi.org/10.1146/annurev-vision-111815-114630

Maniscalco, B., Castaneda, O. G., Odegaard, B., Morales, J., Rajananda, S., & Peters, M. A. K. (2020). *The metaperceptual function: Exploring dissociations between confidence and task performance with type 2 psychometric curves*. PsyArXiv. https://doi.org/10.31234/osf.io/5qrjn

Maniscalco, B., & Lau, H. (2012). A signal detection theoretic approach for estimating metacognitive sensitivity from confidence ratings. *Consciousness and Cognition*, *21*(1), 422–430. https://doi.org/10.1016/j.concog.2011.09.021

Maniscalco, B., & Lau, H. (2014). Signal Detection Theory Analysis of Type 1 and Type 2 Data: Meta- d′ , Response-Specific Meta- d′, and the Unequal Variance SDT Model. In S. M. Fleming & C. D. Frith (Eds.), *The cognitive neuroscience of metacognition*. Springer-Verlag Publishing.

Maniscalco, B., & Lau, H. (2016). The signal processing architecture underlying subjective reports of sensory awareness. *Neuroscience of Consciousness*, *2016*(1), niw002. https://doi.org/10.1093/nc/niw002

Maniscalco, B., Odegaard, B., Grimaldi, P., Cho, S. H., Basso, M. A., Lau, H., & Peters, M. A. K. (2021). Tuned inhibition in perceptual decision-making circuits can explain seemingly suboptimal confidence behavior. *PLoS Computational Biology*, *17*(3), e1008779. https://doi.org/10.1371/journal.pcbi.1008779

Maniscalco, B., Peters, M. A. K., & Lau, H. (2016). Heuristic use of perceptual evidence leads to dissociation between performance and metacognitive sensitivity. *Attention, Perception & Psychophysics*, *78*(3), 923–937. https://doi.org/10.3758/s13414-016-1059-x

Maril, A., Simons, J. S., Mitchell, J. P., Schwartz, B. L., & Schacter, D. L. (2003). Feeling-of-knowing in episodic memory: An event-related fMRI study. *NeuroImage*, *18*(4), 827–836.

Maril, A., Simons, J. S., Weaver, J. J., & Schacter, D. L. (2005). Graded recall success: An event-related fMRI comparison of tip of the tongue and feeling of knowing. *NeuroImage*, *24*(4), 1130–1138. https://doi.org/10.1016/j.neuroimage.2004.10.024

Maril, A., Wagner, A. D., & Schacter, D. L. (2001). On the tip of the tongue: An event-related fMRI study of semantic retrieval failure and cognitive conflict. *Neuron*, *31*(4), 653–660. https://doi.org/10.1016/s0896-6273(01)00396-8

Masson, M. E. J., & Rotello, C. M. (2009). Sources of bias in the Goodman-Kruskal gamma coefficient measure of association: Implications for studies of metacognitive processes. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *35*(2), 509–527. https://doi.org/10.1037/a0014876

McCurdy, L. Y., Maniscalco, B., Metcalfe, J., Liu, K. Y., de Lange, F. P., & Lau, H. (2013). Anatomical coupling between distinct metacognitive systems for memory and visual perception. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *33*(5), 1897–1906. https://doi.org/10.1523/JNEUROSCI.1890-12.2013

McNicol, D. (2005). *A primer of signal detection theory*. Erlbaum Inc.

Mehta, P. (2021). *Celebrity-Face-Recognition-Dataset* [Python]. https://github.com/prateekmehta59/Celebrity-Face-Recognition-Dataset (Original work published 2017)

Metcalfe, J. (1986). Feeling of knowing in memory and problem solving. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *12*(2), 288–294. https://doi.org/10.1037/0278-7393.12.2.288

Metcalfe, J. (1993). Novelty monitoring, metacognition, and control in a composite holographic associative recall model: Implications for Korsakoff amnesia. *Psychological Review*, *100*(1), 3–22. https://doi.org/10.1037/0033-295x.100.1.3

Metcalfe, J., & Schwartz, B. L. (2016). The Ghost in the Machine. In J. Dunlosky & S. K. Tauber (Eds.), *The Oxford Handbook of Metamemory*. Oxford University Press. http://www.oxfordhandbooks.com/view/10.1093/oxfordhb/9780199336746.001.0001/oxfordhb-9780199336746-e-19

Metcalfe, J., Schwartz, B. L., & Bloom, P. A. (2017). The tip-of-the-tongue state and curiosity. *Cognitive Research: Principles and Implications*, *2*. https://doi.org/10.1186/s41235-017-0065-4

Metcalfe, J., Schwartz, B. L., & Joaquim, S. G. (1993). The cue-familiarity heuristic in metacognition. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *19*(4), 851–861. https://doi.org/10.1037//0278-7393.19.4.851

Metcalfe, J., & Shimamura, A. P. (1994). *Metacognition: Knowing about knowing* (pp. xiii, 334). The MIT Press.

Michel, M., Beck, D., Block, N., Blumenfeld, H., Brown, R., Carmel, D., Carrasco, M., Chirimuuta, M., Chun, M., Cleeremans, A., Dehaene, S., Fleming, S. M., Frith, C., Haggard, P., He, B. J., Heyes, C., Goodale, M. A., Irvine, L., Kawato, M., … Yoshida, M. (2019). Opportunities and challenges for a maturing science of consciousness. *Nature Human Behaviour*, *3*(2), 104–107. https://doi.org/10.1038/s41562-019-0531-8

Miller, T. M., & Geraci, L. (2014). Improving metacognitive accuracy: How failing to retrieve practice items reduces overconfidence. *Consciousness and Cognition*, *29*, 131–140. https://doi.org/10.1016/j.concog.2014.08.008

Mitchum, A. L., Kelley, C. M., & Fox, M. C. (2016). When asking the question changes the ultimate answer: Metamemory judgments change memory. *Journal of Experimental Psychology. General*, *145*(2), 200–219. https://doi.org/10.1037/a0039923

Morales, J., Lau, H., & Fleming, S. M. (2018). Domain-General and Domain-Specific Patterns of Activity Supporting Metacognition in Human Prefrontal Cortex. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *38*(14), 3534–3546. https://doi.org/10.1523/JNEUROSCI.2360-17.2018

Morgan, G., Kornell, N., Kornblum, T., & Terrace, H. S. (2014). Retrospective and Prospective Metacognitive Judgments in Rhesus Macaques (Macaca mulatta). *Animal Cognition*, *17*(2), 249–257. https://doi.org/10.1007/s10071-013-0657-4

Nagel, T. (1974). What Is It Like to Be a Bat? *The Philosophical Review*, *83*(4), 435–450. JSTOR. https://doi.org/10.2307/2183914

Nelson, T. O. (1984). A comparison of current measures of the accuracy of feeling-of-knowing predictions. *Psychological Bulletin*, *95*(1), 109–133.

Nelson, T. O. (2000). Consciousness, self-consciousness, and metacognition. *Consciousness and Cognition*, *9*(2 Pt 1), 220–223; discussion 231-242. https://doi.org/10.1006/ccog.2000.0439

Nelson, T. O., & Dunlosky, J. (1992). How Shall We Explain the Delayed-Judgment-Of-Learning Effect? *Psychological Science*, *3*(5), 317–319. https://doi.org/10.1111/j.1467-9280.1992.tb00681.x

Nelson, T. O., Leonesio, J., Shimamura, A. P., Landwehr, R. F., & Narens, L. (1982). Overlearning and the feeling of knowing. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *8*(4), 279–288. https://doi.org/10.1037/0278-7393.8.4.279

Nelson, T. O., & Narens, L. (1980). Norms of 300 general-information questions: Accuracy of recall, latency of recall, and feeling-of-knowing ratings. *Journal of Verbal Learning & Verbal Behavior*, *19*(3), 338–368. https://doi.org/10.1016/S0022-5371(80)90266-2

Nelson, T. O., & Narens, L. (1990). Metamemory: A Theoretical Framework and New Findings. *Psychology of Learning and Motivation*, *26*, 125–173. https://doi.org/10.1016/S0079-7421(08)60053-5

Ni, A. M., Ray, S., & Maunsell, J. H. R. (2012). Tuned Normalization Explains the Size of Attention Modulations. *Neuron*, *73*(4), 803–813. https://doi.org/10.1016/j.neuron.2012.01.006

Odegaard, B., Chang, M. Y., Lau, H., & Cheung, S.-H. (2018). Inflation versus filling-in: Why we feel we see more than we actually do in peripheral vision. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *373*(1755), 20170345. https://doi.org/10.1098/rstb.2017.0345

Pannu, J. K., Kaszniak, A. W., & Rapcsak, S. Z. (2005). Metamemory for faces following frontal lobe damage. *Journal of the International Neuropsychological Society: JINS*, *11*(6), 668–676. https://doi.org/10.1017/S1355617705050873

Papageorgiou, C., & Wells, A. (2003). An Empirical Test of a Clinical Metacognitive Model of Rumination and Depression. *Cognitive Therapy and Research*, *27*(3), 261–273. https://doi.org/10.1023/A:1023962332399

Pappas, B. A., Sunderland, T., Weingartner, H. M., Vitiello, B., Martinson, H., & Putnam, K. (1992). Alzheimer's disease and feeling-of-knowing for knowledge and episodic memory. *Journal of Gerontology*, *47*(3), P159-164. https://doi.org/10.1093/geronj/47.3.p159

Perfect, T. J. (2002). When does eyewitness confidence predict performance? In *Applied metacognition* (pp. 95–120). Cambridge University Press. https://doi.org/10.1017/CBO9780511489976.006

Peters, M. A. K., Thesen, T., Ko, Y. D., Maniscalco, B., Carlson, C., Davidson, M., Doyle, W., Kuzniecky, R., Devinsky, O., Halgren, E., & Lau, H. (2017). Perceptual confidence neglects decision-incongruent evidence in the brain. *Nature Human Behaviour*, *1*, 0139. https://doi.org/10.1038/s41562-017-0139

Pleskac, T. J., & Busemeyer, J. R. (2010). Two-stage dynamic signal detection: A theory of choice, decision time, and confidence. *Psychological Review*, *117*(3), 864–901. https://doi.org/10.1037/a0019737

Pouget, A., Drugowitsch, J., & Kepecs, A. (2016). Confidence and certainty: Distinct probabilistic quantities for different goals. *Nature Neuroscience*, *19*(3), 366–374. https://doi.org/10.1038/nn.4240

Pournaghdali, A., & Schwartz, B. L. (2020). Continuous flash suppression: Known and unknowns. *Psychonomic Bulletin & Review*, *27*(6), 1071–1103. https://doi.org/10.3758/s13423-020-01771-2

Pournaghdali, A., Schwartz, B. L., Hays, J. S., & Soto, F. (in revision). *Sensitivity vs. Awareness Curve: A Novel Model-Based Analysis to Uncover the Processes Underlying Nonconscious Perception* [Preprint]. PsyArXiv. https://doi.org/10.31234/osf.io/akem2

Rahnev, D., Desender, K., Lee, A. L. F., Adler, W. T., Aguilar-Lleyda, D., Akdoğan, B., Arbuzova, P., Atlas, L. Y., Balcı, F., Bang, J. W., Bègue, I., Birney, D. P., Brady, T. F., Calder-Travis, J., Chetverikov, A., Clark, T. K., Davranche, K., Denison, R. N., Dildine, T. C., … Zylberberg, A. (2020). The Confidence Database. *Nature Human Behaviour*, *4*(3), 317–325. https://doi.org/10.1038/s41562-019-0813-1

Ratcliff, R. (2002). A diffusion model account of response time and accuracy in a brightness discrimination task: Fitting real data and failing to fit fake but plausible data. *Psychonomic Bulletin & Review*, *9*(2), 278–291. https://doi.org/10.3758/bf03196283

Ratcliff, R., & McKoon, G. (2008). The Diffusion Decision Model: Theory and Data for Two-Choice Decision Tasks. *Neural Computation*, *20*(4), 873–922. https://doi.org/10.1162/neco.2008.12-06-420

Ratcliff, R., & Starns, J. J. (2009). Modeling confidence and response time in recognition memory. *Psychological Review*, *116*(1), 59–83. https://doi.org/10.1037/a0014086

Reggev, N., Zuckerman, M., & Maril, A. (2011). Are all judgments created equal? An fMRI study of semantic and episodic metamemory predictions. *Neuropsychologia*, *49*(5), 1332–1342. https://doi.org/10.1016/j.neuropsychologia.2011.01.013

Rhodes, M. G., & Tauber, S. K. (2011). The influence of delaying judgments of learning on metacognitive accuracy: A meta-analytic review. *Psychological Bulletin*, *137*(1), 131–148. https://doi.org/10.1037/a0021705

Rosenthal, D. (2019). Consciousness and confidence. *Neuropsychologia*, *128*, 255–265. https://doi.org/10.1016/j.neuropsychologia.2018.01.018

Rounis, E., Maniscalco, B., Rothwell, J. C., Passingham, R. E., & Lau, H. (2010). Theta-burst transcranial magnetic stimulation to the prefrontal cortex impairs metacognitive visual awareness. *Cognitive Neuroscience*, *1*(3), 165–175. https://doi.org/10.1080/17588921003632529

Rouy, M., Saliou, P., Nalborczyk, L., Pereira, M., Roux, P., & Faivre, N. (2021). Systematic review and meta-analysis of metacognitive abilities in individuals with schizophrenia spectrum disorders. *Neuroscience & Biobehavioral Reviews*, *126*, 329–337. https://doi.org/10.1016/j.neubiorev.2021.03.017

Sacher, M., Taconnat, L., Souchay, C., & Isingrini, M. (2009). Divided attention at encoding: Effect on feeling-of-knowing. *Consciousness and Cognition*, *18*(3), 754–761. https://doi.org/10.1016/j.concog.2009.04.001

Samaha, J., & Postle, B. R. (2017). Correlated individual differences suggest a common mechanism underlying metacognition in visual perception and visual short-term memory. *Proceedings. Biological Sciences*, *284*(1867), 20172035. https://doi.org/10.1098/rspb.2017.2035

Sandberg, K., Timmermans, B., Overgaard, M., & Cleeremans, A. (2010). Measuring consciousness: Is one measure better than the other? *Consciousness and Cognition*, *19*(4), 1069–1078. https://doi.org/10.1016/j.concog.2009.12.013

Sanders, J. I., Hangya, B., & Kepecs, A. (2016). Signatures of a Statistical Computation in the Human Sense of Confidence. *Neuron*, *90*(3), 499–506. https://doi.org/10.1016/j.neuron.2016.03.025

Schnyer, D. M., Nicholls, L., & Verfaellie, M. (2005). The role of VMPC in metamemorial judgments of content retrievability. *Journal of Cognitive Neuroscience*, *17*(5), 832–846. https://doi.org/10.1162/0898929053747694

Schnyer, D. M., Verfaellie, M., Alexander, M. P., LaFleche, G., Nicholls, L., & Kaszniak, A. W. (2004). A role for right medial prefrontal cortex in accurate feeling-of-knowing judgments: Evidence from patients with lesions to frontal cortex. *Neuropsychologia*, *42*(7), 957–966. https://doi.org/10.1016/j.neuropsychologia.2003.11.020

Schraw, G., Dunkle, M. E., Bendixen, L. D., & Roedel, T. D. (1995). Does a general monitoring skill exist? *Journal of Educational Psychology*, *87*(3), 433–444. https://doi.org/10.1037/0022-0663.87.3.433

Schraw, G., & Nietfeld, J. (1998). A further test of the general monitoring skill hypothesis. *Journal of Educational Psychology*, *90*(2), 236–248. https://doi.org/10.1037/0022-0663.90.2.236

Schwartz, B. L. (1994). Sources of information in metamemory: Judgments of learning and feelings of knowing. *Psychonomic Bulletin & Review*, *1*(3), 357–375. https://doi.org/10.3758/BF03213977

Schwartz, B. L. (1998). Illusory tip-of-the-tongue states. *Memory (Hove, England)*, *6*(6), 623–642. https://doi.org/10.1080/741943371

Schwartz, B. L. (2001). The relation of tip-of-the-tongue states and retrieval time. *Memory & Cognition*, *29*(1), 117–126. https://doi.org/10.3758/bf03195746

Schwartz, B. L. (2006). Tip-of-the-tongue states as metacognition. *Metacognition and Learning*, *1*(2), 149–158. https://doi.org/10.1007/s11409-006-9583-z

Schwartz, B. L. (2008). Working memory load differentially affects tip-of-the-tongue states and feeling-of-knowing judgments. *Memory & Cognition*, *36*(1), 9–19. https://doi.org/10.3758/mc.36.1.9

Schwartz, B. L. (2010). The effects of emotion on tip-of-the-tongue states. *Psychonomic Bulletin & Review*, *17*(1), 82–87. https://doi.org/10.3758/PBR.17.1.82

Schwartz, B. L., Boduroglu, A., & Tekcan, A. İ. (2016). Methodological concerns: The feeling-of-knowing task affects resolution. *Metacognition and Learning*, *11*(3), 305–316. https://doi.org/10.1007/s11409-015-9152-4

Schwartz, B. L., & Cleary, A. M. (2016, June 1). *Tip-of-the-Tongue States, Déjà Vu Experiences, and Other Odd Metacognitive Experiences*. The Oxford Handbook of Metamemory. https://doi.org/10.1093/oxfordhb/9780199336746.013.5

Schwartz, B. L., & Díaz, F. (2014). Quantifying human metacognition for the neurosciences. In *The cognitive neuroscience of metacognition* (pp. 9–23). Springer-Verlag Publishing. https://doi.org/10.1007/978-3-642-45190-4_2

Schwartz, B. L., & Efklides, A. (2012). Metamemory and memory efficiency: Implications for student learning. *Journal of Applied Research in Memory and Cognition*, *1*(3), 145–151. https://doi.org/10.1016/j.jarmac.2012.06.002

Schwartz, B. L., & Jemstedt, A. (2021). The Role of Fluency and Dysfluency in Metacognitive Experiences. In D. Moraitou & P. Metallidou (Eds.), *Trends and Prospects in Metacognition Research across the Life Span: A Tribute to Anastasia Efklides* (pp. 25–40). Springer International Publishing. https://doi.org/10.1007/978-3-030-51673-4_2

Schwartz, B. L., & Metcalfe, J. (1992). Cue familiarity but not target retrievability enhances feeling-of-knowing judgments. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *18*(5), 1074–1083. https://doi.org/10.1037//0278-7393.18.5.1074

Schwartz, B. L., & Metcalfe, J. (2011). Tip-of-the-tongue (TOT) states: Retrieval, behavior, and experience. *Memory & Cognition*, *39*(5), 737–749. https://doi.org/10.3758/s13421-010-0066-8

Schwartz, B. L., & Metcalfe, J. (2014). Tip-of-the-Tongue (TOT) States: Mechanisms and Metacognitive Control. *Tip-of-the-Tongue States and Related Phenomena*, 15–31. https://doi.org/10.1017/CBO9781139547383.002

Schwartz, B. L., & Metcalfe, J. (2017). 2.23 - Metamemory: An Update of Critical Findings. In J. H. Byrne (Ed.), *Learning and Memory: A Comprehensive Reference (Second Edition)* (pp. 423–432). Academic Press. https://doi.org/10.1016/B978-0-12-809324-5.21056-0

Schwartz, B. L., Pillot, M., & Bacon, E. (2014). Contextual information influences the feeling of knowing in episodic memory. *Consciousness and Cognition*, *29*, 96–104. https://doi.org/10.1016/j.concog.2014.08.018

Schwartz, B. L., & Pournaghdali, A. (2016). Metacognition and conscious experience. *The Behavioral and Brain Sciences*, *39*, e195. https://doi.org/10.1017/S0140525X15002253

Schwartz, B. L., & Pournaghdali, A. (2020). Tip-of-the-tongue States: Past and Future. In A. M. Cleary & B. L. Schwartz (Eds.), *Memory Quirks: The Study of Odd Phenomena in Memory* (pp. 207–223). Routledge. https://doi.org/10.4324/9780429264498-16

Schwartz, B. L., & Smith, S. M. (1997). The Retrieval of Related Information Influences Tip-of-the-Tongue States. *Journal of Memory and Language*, *36*(1), 68–86. https://doi.org/10.1006/jmla.1996.2471

Schwartz, B. L., Travis, D. M., Castro, A. M., & Smith, S. M. (2000). The phenomenology of real and illusory tip-of-the-tongue states. *Memory & Cognition*, *28*(1), 18–27. https://doi.org/10.3758/bf03211571

Selker, R., van den Bergh, D., Criss, A. H., & Wagenmakers, E.-J. (2019). Parsimonious estimation of signal detection models from confidence ratings. *Behavior Research Methods*, *51*(5), 1953–1967. https://doi.org/10.3758/s13428-019-01231-3

Shafto, M. A., Burke, D. M., Stamatakis, E. A., Tam, P. P., & Tyler, L. K. (2007). On the Tip-of-the-Tongue: Neural Correlates of Increased Word-finding Failures in Normal Aging. *Journal of Cognitive Neuroscience*, *19*(12), 2060–2070. https://doi.org/10.1162/jocn.2007.19.12.2060

Shanks, D. R. (2017). Regressive research: The pitfalls of post hoc data selection in the study of unconscious mental processes. *Psychonomic Bulletin & Review*, *24*(3), 752–775. https://doi.org/10.3758/s13423-016-1170-y

Shekhar, M., & Rahnev, D. (2021a). The nature of metacognitive inefficiency in perceptual decision making. *Psychological Review*, *128*(1), 45–70. https://doi.org/10.1037/rev0000249

Shekhar, M., & Rahnev, D. (2021b). Sources of Metacognitive Inefficiency. *Trends in Cognitive Sciences*, *25*(1), 12–23. https://doi.org/10.1016/j.tics.2020.10.007

Silbert, N. H., & Thomas, R. D. (2017). Identifiability and testability in GRT with individual differences. *Journal of Mathematical Psychology*, *77*, 187–196. https://doi.org/10.1016/j.jmp.2016.08.002

Sinanaj, I., Cojan, Y., & Vuilleumier, P. (2015). Inter-individual variability in metacognitive ability for visuomotor performance and underlying brain structures. *Consciousness and Cognition*, *36*, 327–337. https://doi.org/10.1016/j.concog.2015.07.012

Song, C., Kanai, R., Fleming, S. M., Weil, R. S., Schwarzkopf, D. S., & Rees, G. (2011). Relating inter-individual differences in metacognitive performance on different perceptual tasks. *Consciousness and Cognition*, *20*(4), 1787–1792. https://doi.org/10.1016/j.concog.2010.12.011

Soto, F. A., Vucovich, L., Musgrave, R., & Ashby, F. G. (2015). General recognition theory with individual differences: A new method for examining perceptual and decisional interactions with an application to face perception. *Psychonomic Bulletin & Review*, *22*(1), 88–111. https://doi.org/10.3758/s13423-014-0661-y

Soto, F. A., Zheng, E., Fonseca, J., & Ashby, F. G. (2017). Testing Separability and Independence of Perceptual Dimensions with General Recognition Theory: A Tutorial and New R Package (grtools). *Frontiers in Psychology*, *8*, 696. https://doi.org/10.3389/fpsyg.2017.00696

Tauber, S. K., Dunlosky, J., Rawson, K. A., Rhodes, M. G., & Sitzman, D. M. (2013). General knowledge norms: Updated and expanded from the Nelson and Narens (1980) norms. *Behavior Research Methods*, *45*(4), 1115–1143. https://doi.org/10.3758/s13428-012-0307-9

Tsuchiya, N., & Koch, C. (2005). Continuous flash suppression reduces negative afterimages. *Nature Neuroscience*, *8*(8), 1096–1101. https://doi.org/10.1038/nn1500

Tye, M. (1986). The Subjective Qualities of Experience. *Mind*, *95*(377), 1–17.

Vaccaro, A. G., & Fleming, S. M. (2018). Thinking about thinking: A coordinate-based meta-analysis of neuroimaging studies of metacognitive judgements. *Brain and Neuroscience Advances*, *2*, 2398212818810591. https://doi.org/10.1177/2398212818810591

Veenman, M. V. J., Elshout, J. J., & Meijer, J. (1997). The generality vs domain-specificity of metacognitive skills in novice learning across domains. *Learning and Instruction*, *7*(2), 187–209. https://doi.org/10.1016/S0959-4752(96)00025-4

Vigliocco, G., Antonini, T., & Garrett, M. F. (1997). Grammatical gender is on the tip of Italian tongues. *Psychological Science*, *8*(4), 314–317. https://doi.org/10.1111/j.1467-9280.1997.tb00444.x

Warriner, A. B., & Humphreys, K. R. (2008). Learning to fail: Reoccurring tip-of-the-tongue states. *Quarterly Journal of Experimental Psychology (2006)*, *61*(4), 535–542. https://doi.org/10.1080/17470210701728867

Yaniv, I., & Meyer, D. E. (1987). Activation and metacognition of inaccessible stored information: Potential bases for incubation effects in problem solving. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *13*(2), 187–205. https://doi.org/10.1037//0278-7393.13.2.187

Yokoyama, O., Miura, N., Watanabe, J., Takemoto, A., Uchida, S., Sugiura, M., Horie, K., Sato, S., Kawashima, R., & Nakamura, K. (2010). Right frontopolar cortex activity correlates with reliability of retrospective rating of confidence in short-term recognition memory performance. *Neuroscience Research*, *68*(3), 199–206. https://doi.org/10.1016/j.neures.2010.07.2041

Yu, S., Pleskac, T. J., & Zeigenfuse, M. D. (2015). Dynamics of postdecisional processing of confidence. *Journal of Experimental Psychology. General*, *144*(2), 489–510. https://doi.org/10.1037/xge0000062

Appendices

Appendix A: List of General Knowledge Questions Created for This Study

Question	Correct Response
What is the name of the long sleep some animals go through during a hot or dry period?	Aestivation
What is the current name of the highest mountain in north America?	Denali
In what year, did Miami Heat win NBA championship for the first time?	2006
What is the last name of the new England patriots head coach who won the most Superbowl championship in American football history?	Belichick
What is the name of the baseball team homed in Boston Massachusetts?	Red sox
What is the last name of the actor who played "Kramer" in the tv show Seinfeld?	Richards
What is the last name of the actor who played the main character in the tv show "Curb Your Enthusiasm"?	David
What is the capital of Iran?	Tehran
What is the last name of the American swimmer holding the all-time records for Olympic gold medals?	Phelps
What is the last name of the author of Twilight?	Meyer
What national soccer team won the 2010 FIFA world cup?	Spain
In what us state is the Mount Rushmore located?	South Dakota
What is the last name of the actor who is famous for portraying Mr. Bean?	Atkinson
What is the last name of the actor who played as the eleventh doctor in the Doctor Who series?	Smith
What is the name of the main antagonist (villain) in “The Lord of the Rings” book trilogy?	Sauron
What is the last name of the director of the movie "Munich"?	Spielberg
What is the capital city of state of Florida?	Tallahassee

What is the name of the school of witchcraft and wizardry in “The Harry Potter” book series?	Hogwarts
What is the name of the central character of Homer's Iliad?	Achilles
What is the capital of New Zealand	Wellington
Of what state is the city of Austin the capital?	Texas
What is the highest mountain in Africa?	Kilimanjaro
What is the second highest mountain in the world, after Mount Everest?	K2
In what city is the main campus of the University of Wisconsin?	Madison
What is the last name of the male athlete who has gotten the most gold medals at the 100 meter dash at the Olympics?	Bolt
What is the last name of john McCain’s running mate in 2008 presidential election?	Palin
In what month is a ‘leap’ day added every four years?	February
What is a frog larva called?	Tadpole
What is the last name of the actor who played the character of "Neo" in The Matrix trilogy?	Reaves
What is the last name of the former English soccer player who is an owner of "Inter Miami" soccer team?	Beckham
What national soccer team won the most FIFA World Cup title?	Brazil
What is the last name of the US president who was involved with Watergate scandal?	Nixon
What is the last name of the Spanish tennis player who won 12 French Open men's singles championships?	Nadal
What is the name of the mountain range in the west of Iran?	Zagros
In what country is the city of Istanbul located?	Turkey
What is the first name of the dark queen in the tv show “Once Upon a Time”?	Regina
What is the first name of the eldest evil step sister in Cinderella (1950)?	Drizella
What is the name of the princess from “The Princess and The Frog”?	Tiana
What is the name of the triangle with no equal angles and no equal sides?	Scalene

What is the last name of the German Formula One driver who won 91 Grand Prix races?	Schumacher
What is the name of the US city that is known as "the biggest little city in the world"?	Reno
What is the last name of the US president during World War 1?	Wilson
What is the last name of the American sisters who won total of 30 single grand slams in tennis?	Williams
In what us state is Tonto national forest located?	Arizona
What is the last name of the main male character in the tv show "Breaking Bad"?	White
Who is the leader of the Decepticons in the "Transformers" movie series?	Megatron
Who is the leader of "Tethered" in the movie "Us" (2019)?	Red
What is the name of the villainous robots in the tv show "Battlestar Galactica"?	Cylons
What is the last name of the basketball player who scored the most points in NBA history?	Abdul-jabbar
What is the name of the small European country that is surrounded by Belgium, France and Germany?	Luxembourg
In what Indian city is "Taj Mahal" located?	Agra
What is the common title of the monarchs of ancient Egypt?	Pharaoh
What is the last name of the actor who played "Dr. Schultz" in the movie "Django Unchained"?	Waltz
What is the capital of Ecuador?	Quito
What is the monetary currency in Russia?	Ruble
What is the last name of the author of "In Search of Lost Time"?	Proust
What is the last name of the British prime minister at the beginning of World War 2?	Chamberlain
What is the last name of the host of "The Daily Show" before Trevor Noah?	Stewart
Who was the ancient Greek doctor associated with the oath doctors make today?	Hippocrates
What is the last name of the movie actor who portrayed Captain America in The Avenger movies?	Evans
In what us state is The Gateway Arch located?	Missouri

In what language, did Dante write “The Divine Comedy”?	Italian
What is the name of the space probe that is the farthest man-made object from earth?	Voyager
What is the first name of the character who said "one does not simply walk into Mordor"?	Boromir
What is the last name of the male singer of “Space Oddity”?	Bowie
What is the last name of the actor who portrayed James Bond in the movie “Skyfall”?	Craig
In what US city, the declaration of independence was first drafted?	Philadelphia
What is the last name of the lead singer in the rock band “Metallica”?	Hetfield
What is the name of the single particle of light?	Photon
What movie production company owns “Fast and Furious” movie franchise?	Universal
What is the capital of state of California?	Sacramento
Which month is referred to as men's health awareness month?	November
What is the name of the last emperor of China?	Puyi
What is the name of the artificial waterway in Egypt, connecting the Mediterranean Sea to the Red Sea?	Suez
What is the name of the largest gulf in the world?	Mexico
What is the name of the smallest continent on earth?	Australia
What is the last name of the first superhero known as “The Flash”?	Garrick
What is the last name of the captain of “USS Enterprise” in the tv show “Star Trek: The Next Generation”?	Picard
What is the name of a sheep in its first year of life?	Lamb
What is USA national flower?	Rose
What is the monetary currency in Uruguay?	Peso
What is the last name of the first rapper to win the Pulitzer Prize for music?	Lamar
What is the monetary currency in Switzerland?	Franc
What is the name of the closest galaxy to Milky Way?	Andromeda

What is the name of the mountain that is the site of the throne of Zeus in Greek mythology?	Olympus
What is the name of the largest lake in the world?	Caspian
What is the name of the constellation that looks like a lion?	Leo
What is the name of SpongeBob's pet?	Gary
What is the name of the Russian spacecraft that used to transfer US astronauts to the international space station?	Soyuz
What is the first name of the pig in Looney Tunes?	Porky
What is the name of the ninja master rat in the "Teenage Mutant Ninja Turtles"?	Splinter
What is the name of NBA basketball team based in Cleveland?	Cavaliers
What is the last name of female novelist who was portrayed in the movie "The Hours"?	Woolf
What is the last name of Scooby doo's best friend?	Rogers
What is the home city of NBA 2019 champion?	Toronto
What is the last name of fictional archaeologist who was portrayed by Harrison Ford?	Jones
What is the last name of the writer of "Murder on the Orient Express"?	Christie
What is the last name of the speaker of US House of Representatives from 2011 to 2015?	Boehner
What is the last name of the signer known as "Lady Gaga"?	Germanotta
What is the last name of the founder of Amazon?	Bezos
What is the last name of the founder and current CEO of Facebook?	Zuckerberg
What is the name of Burger King's signature burger?	Whopper
"Agent 47" is part of which video game franchise?	Hitman
What is the last name of the actor who played "Doc Holliday" in the 1993 movie "Tombstone"?	Kilmer
For which country is the "Taka" the monetary unit?	Bangladesh
What native American nation in the US has the largest membership?	Navajo
What is the last name of democratic nominee in 2000 presidential election?	Gore

What is the last name of the actor who portrayed “Jack Sparrow” in “The Pirates of the Caribbean” movie series?	Depp
What is the last name of the first woman to be prime minister of the United Kingdom?	Thatcher
What is the last name of the character portrayed by Keven Costner in the movie “The Untouchables”?	Ness
For what country is the city of Lima the capital?	Peru
What is the last name of the author of “War and Peace”?	Tolstoy
What is the last name of the current host of “Real Time” at HBO?	Maher
What is the last name of the us president who signed “The Medicare Act” into law?	Johnson
What is the name of the single particle of light?	Photon
What is the last name of US senate majority leader from 2007 to 2015?	Reid
What is the last name of the rapper known as “Killer Mike”?	Render
What is the last name of the main protagonist of the video game franchise “Tomb Raider”?	Croft
What is the name of streaming service that owns tv shows such as “The Handmaid's Tale” and “Castle Rock”?	Hulu
What is the last name of the regional manager in the tv show “The Office” portrayed by Steve Carell?	Scott
What is the last name of the DJ known as “Deadmau5”?	Zimmerman
What is the last name of the character that was portraited by Leonardo DiCaprio in the movie “The Revenant”?	Glass
What is the capital of Brazil?	Brasilia
What is the last name of Huckleberry Finn’s best friend?	Sawyer
What is the last name of the last leader of the Soviet Union?	Gorbachev
What is last name of the founder of the rock band “The Beatles”?	Lennon

Appendix B: List of Illusory Questions Created for This Study

Question	Provided Alternative
What is the name of the planet in the Solar System that is larger than Sun?	Jupiter
In what year did the USA send the first man to Mars?	1973
In what US city is “The Shard Museum” located?	Salem
What is the last name of the British navigator who discovered the continent of Asia in 1100s?	Bruce
What is the last name of the author of the novel “Lake Far from My House”?	Shimon
What is the last name of the director of the movie “One Hour to Everything”?	Aronofsky
In what movie John Cusack portrayed William Hanson?	Serendipity
What is the last name of the actress who portrayed John Nash’s mother in the movie “A Beautiful Mind”?	Kidman
In what US state is the “Khir Fakkan Monument” located?	Ohio
What is the last name of the actor who portrayed Richard Feynman in the movie “The Theory of Everything”?	Thewlis
What US city hosted 1992 summer Olympics?	Atlanta
What is the capital of Riyadh?	Jeddah
What is the last name of the astronomer who discovered the great crater on Jupiter?	Haise
What is the last name of the first man who traveled beyond the boundaries of Solar System?	Lovell
In what European city is “Craters of the Moon” located?	Lisbon
What is the last name of the only woman to sign the Declaration of Independence?	Hopper
In what European city was “Herman Melville” born?	Belfast
What is the last name of the current prime minister of Costa Rica?	Rodriguez
What is the last name of the American Oscar wining director of "The Sales"?	Coppola
In what Middle Eastern city is “Ma'alwird National Park” located?	Isfahan

What is the capital of Lagaria?	Algiers
In what US city is “Warwick University” located?	Tucson
What is the last name of the character portrayed by Judi Dench in the tv show “American Horror Story: Coven”?	Day
In what movie Gillian Anderson portrayed Sister Ann?	Flight
What is the last name of the character portrayed by Jessica Chastain in the movie “The Reader”?	Berg
In what movie Brad Pitt portrayed Johnny Cash?	Seven
Of which ancient country was Volgograd the capital?	Silesia
In what year did the white revolution happen in the USA?	1890
In what country is “Sedarmsington Monument” located?	Montenegro
What is the last name of US national athlete in 2010?	Adrian
What is the last name of the character that was played by Spike Lee in a Star Trek movie?	Sisko
In what country is “Temple of Umjir” located?	Mangolia
What is the capital of Bormea?	Bali
What is the name of the only mountain in Belarus?	Sabalan
What is the name of the African religion founded by Obi Haalagi?	Sefoline
In what US state is “Mount Zugspitze” located?	Arkansas
What is the last name of US prime minister during World War 1?	Marshall
What is the name of the Canadian province that starts with the letter z?	Zurich
What is the name of the only primate species that lives under the water?	Proboscis
What is the name of the movie, for which sir Ian McKellen received an Oscars in acting?	Stardust
What is the name of the Egyptian philosopher who introduced the Pythagorean Theorem for the first time?	Ptahhotep
What is the last name of the person who assassinated president Theodore Roosevelt?	Guiteau

What is the last name of the American poet who received two Nobel Prizes in literature?	Sanger
What is the last name of the character portrayed by Amy Adams in the movie “Joy”?	Jennifer
In what state is Washington Dc located?	Maryland
In what year did Will Smith win an Oscar for his acting for playing Muhammad Ali in the movie “Ali”?	2001
In what US city is “Fisherman's Bastion Museum” located?	Fresno
What animal helped Prince Philip to find Sleeping Beauty and wake her up?	Fox
What is the last name of the author of the novel “The Adventures of Don Thomasina”?	Pirlo
In what US city is “Pitti Palace” located?	Tulsa
In what US city is “Cologne Cathedral” located?	Dallas
What is the last name of the actor who played Morgoth in The Lord of The Rings trilogy?	Holm
What is the name of the planet Mercury’ s moon?	Callisto
In what US state is “Mount Damavand” located?	West virginia
What is the last name of the actress who portrayed Maggie Greene in the tv show “Grimm”?	Holden
What is the last name of the actor who received three Golden Raspberry awards for worst supporting actor?	Leto
What is the last name of the character portrayed by Kate Winslet in the movie “Crimson Peak”?	Sharpe
In what European city is “Big Bend Park” located?	Vilnius
What major US city is served by Franklin Roosevelt airport?	Denver
What is the last name of the actor who portrayed Paul Edgecomb in the movie “The Shawshank Redemption”?	Demunn
In what year, did Robert f. Kennedy get elected as the president of the United States?	1953
What is the last name of the director of the movie “O Father, Where Are Thou”?	Cohen

What is the last name of the actress who portrayed Scarlett Picon in the tv show "Picon"?	Mirren
What is the last name of the character portrayed by Robert De Niro in the movie "Serpico"?	Lane
What is the only African country that lists German as an official language?	Morocco
What is the only city of over a million people in Iceland?	Reykjavik
What is the last name of the character portrayed by Jake Gyllenhaal in the movie "J. Edgar"?	Tolson
In what country is "Mount Iggrayl" located?	Guyana
What is the capital of East Russia?	Kazan
What is the last name of the character portrayed by Al Pachino in the movie "Cape Fear"?	Cady
What is the name of Steven King's book that happens in the International Space Station?	The mangler
What is the first name of the character in the Game of Thrones series that was played by Ewan McGregor?	Jorah
What is the name of the ancient Greek mathematician who first defined number "zero"?	Antiphon
What is the last name of the chemist who transformed coal to gold for the first time?	Hayyan
Who is the last name of the author of the French novel, "La Chienne De Froid"?	Sartre
In which major European city is Glandine airport located?	Ankara
What is the first movie created by tom Borsten?	Bulleit
What is the name of the legendary floating island in ancient Greece?	Delos
What language is spoken on the east Indies country of San Lorenzo?	Spanish
What is the last name of the author of the novel "Me and Infinite Worlds"?	Veii
What is the name of the current president of Canada?	Freeland
What is the name of the current US prime minister?	Pompeo
What is the name of the movie by Christopher Nolan that won Oscars for the best picture in 2015?	Interstellar

In what US state is “Alhambra” located?	Alaska
What is the first name of the heroic innkeeper in the movie Seems Like Old Times Again?	Glenda
What is the unit of measurement that refers to the weight of 2 cubic feet of iron?	Firkin
What is the last name of the Nobel-winning scientist who discovered the element Tryinium?	Pauling
What is the last name of the singer who received five Golden Raspberry awards for worst song of the year?	Grande
What is the last name of the actor who played Tom Bombadil in the hobbit trilogy?	Turner
In what US state is “Hagia Andronica Tower” located?	Connecticut
What percent of antarctica is owned by Sweden?	12
What is the last name of the actor who portrayed Doctor Fate in the movie “Green Lantern”?	Strong
What is the name of the capital city of Girne?	Larnaca
In what US state is Danube River located?	Idaho
What is the name of the country that was defeated militarily by the USA in 1987 and subsequently became a US territory?	Guam
For what African country is the city of "Al Ain" the capital?	Ethiopia
What is the last name of the first American scientist who received a Nobel prize in astronomy?	Sagan
What is the name of the warship that sank the Titanic in 1912?	Brandenburg
What is the last name of the character portrayed by Jennifer Lawrence in the movie “Nocturnal Animals”?	Morrow
Of which country is Minervia the capital?	Macedonia
What is the name of the US territory that will officially become a US state in 2030?	Midway Islands
In what US state is Zinsmeister College located?	Minnesota
What is the first name of the character portrayed by Russell Crowe in the movie “The Master”?	Val

What is the last name of the first woman to become the US secretary of defense?	Carlucci
In what Middle Eastern city is “Stahl House” located?	Haifa
In what language did the poet “La Piqûre” write in?	Haitian creole
In what year did Hong Kong become the official capital of China?	2008
What is the first name of Darth Vader's father in the Star Wars saga?	Mace
What nation won the gold medal for karate in the 2016 Olympics?	Japan
What is the name of the country that invaded Canada in 1985?	England
In what us state is “Laverso Gardens” located?	Iowa
What is the last name of the American soccer player who scored three goals in the "FIFA Women's World Cups” final game against Japan in 2011?	Morgan
What is the name of the other planet in our Solar System aside from Earth that contains life?	Mars
What is the last name of the 48th president of the United States?	Obama
In which South American country some people still speak in Tehuelche language?	Argentina
What is the last name of the actor who portrayed Bruce Banner’s step father in the movie “The Incredible Hulk”?	Nicholson
What is the name of the US city along the coast of Caspian sea?	Ogunquit
In what country is “Evohr Temple” located?	Yemen
What is the last name of the American author who wrote "The Purchase of The North Pole"?	Twain
What South American country joined axis countries during World War 2?	Liberia
What is the name of the only kind of living reptile that flies?	Skink
In what country is “The Putrid Desert” located?	Rwanda
What is the name of the only kind of sea turtle that lays its eggs under water?	Loggerhead
What is the only species of bird that can breathe underwater?	Penguin
What is the last name of the only US president who got elected 5 times?	Roosevelt
What is the name of the sea in the borders of Mongolia?	Bering

What is the last name of the author of the novel “The Master Name Leo”?	Summer
What is the last name of the only male actor who won 4 Oscars in acting?	Brennan
What is the last name of the composer who wrote the opera L’eglise Blanche?	Puccini
What is the only country that borders Jatikistan?	Pakistan
What is the last name of the American legendary soccer player who played for FC Barcelona in 2000s?	Donovan
What is the last name of the German physicist who won 3 Nobel Prizes in physics during his lifetime?	Planck
In what European city is “Montezuma Castle” located?	Sofia
What is the first name of Mrs. Potts husband in the movie Beauty and the Beast?	Tom
What is the last name of the only Argentinian actress who received academy awards for acting?	Ortega
What is the last name of the author of the novel “LA: I Love You”?	Vander
In what country do people speak Tengwar?	Chad
In what country is the city of “Wisnta” located?	Slovenia
What is the name of the desert in the middle of Switzerland?	Tabernas
In what year will New York City no longer be home to the United Nations?	2030
In what Middle Eastern city is “The Temple of Zurish” located?	Fujairah
What is the last name of the character portrayed by Robin Williams in the movie “the Fighter”?	Ward
What is the name of the 12th planet in the Solar System?	Proxima
In what Middle Eastern city is “Hollyhock House” located?	Beirut
What is the last name of the man who invented the so-called “artificial gill?”	Cousteau
In what European city is “the Gatesville Bridge” located?	Yerevan
What is the last name of the first female athlete who was named US national athlete of the year?	Morgan
What is the last name of the Canadian author who wrote the novel The Last Bucket?	Boyden
In what US city is “Villa Savoye” located?	Medford

What is the last name of the director of the movie “The Darkest Movie”?	Chaplin
In what US city is “Grand Bur Church” located?	Des moines
What is the last name of the commander of confederate army in the second US civil war in 1900?	Davis
What is the name of the movie that depicts the life of Tom Hanks?	The captain
In what year did Stephen Hawking win the Nobel Prize in physics?	2015
For what state is the city of Chicago the capital?	Indiana
What is the capital city of the State of New England?	Montpelier
In what European city is “Space Needle” located?	Brava
What is the last name of the first astronaut who landed an asteroid?	Hurley
What is the only Canadian city whose football team has won a Superbowl?	Toronto
What is the name of the current Ottoman king?	Orhan
In what year will Mexico officially adopt us dollar as its monetary currency?	2030
What is the only species of amphibian that has true flight?	Wallace frog
What is the last name of the character portrayed by Jessica Lange in the movie “Misery”?	Sindell
What is the first name of the character in the "Lost" tv show that was played by Billy Boyd?	Charlie
In what US state is Mount Forbes located?	North dakota
In what year did Israel become part of Nato?	2000
What is the name of the only type of cat native to Australia?	Munchkin
What is the last name of the Roman chemist who discovered color blue?	Lucretius
What is the name of Odin's father in Greek mythology?	Aphrodite
What is the name of the only remaining US colony in Africa?	Cali
What is the name of the only American journalist who won 5 Pulitzer Prizes for journalism?	Greenwald
In what year did Puerto Rico become a us state?	1990
What is the last name of the author of the book “The Big Brother, Never Again”?	Nahili

For which country is the Jaque the monetary unit?	Senegal
What country sent a human to Moon in 2000s?	China
What is the name of the lowest layer of Earth's atmosphere just below Troposphere?	Mesosphere
In what country is “The Church of Droqaceris” located?	Angola
In what US state was scuba diving invented?	California
What is the name of the state in the United States that starts with the letter b?	Baltimore
What percentage of Amazon rainforest is owned by Canada?	10
What Indian city is linked to Sri Lanka by a suspension bridge?	Kolkata
In what year did hurricane Tabitha strike the east coast of Texas with category 4 winds?	1960
In what European city is “Mackinac Bridge” located?	Bratislava
What is the last name of the actress who played Aladdin's mother in the animated movie "Aladdin" in 1992?	Ryan
In what year did the Florida become independent from Spain?	1804
What is the capital of Karakistan?	Khujand
What is the last name of the basketball player who hit the three-point shot in overtime to win the championship in 1993?	Grant
What is the last name of the author of the novel “Brindille”?	Stendhal
In what year did USA men’s soccer win the soccer World Cup?	1990
In what year did the Montreal Expos win the world series?	1976
What is the last name of the author of the book “A Man from Cleveland”?	Campbell
What is the name of the kind of car that uses oxygen as the fuel?	Oxygenet
What is the last name of the director of the movie “The High Peak”?	Kubrick
What is the last name of American mathematician who won the Nobel Prize in mathematics in 2018?	Johnson
What is the name of the city in Serbia that lies on the coast of the BLack Sea?	Belgrade
In what tv show Anna Torv portrayed agent Julia Ford?	Dollhouse

What is the name of the only movie that won 13 Oscars?	Ben-hur
In what European city is “Zerbin Tower” located?	Dresden
In what country is “Tralton River” located?	Croatia
What is the last name of the director of the movie “March of the Living Dead”?	Lynch

VITA

ALI POURNAGHDALI

EDUCATION AND HONORS

2021	J. Frank Yates Student Conference Award, from Psychonomic Society
2020	Griffith Memorial Award in Psychology, from The Southern Society for Philosophy and Psychology
2020	The Southern Society for Philosophy and Psychology Graduate Students Travel Award
2018	Masters in Psychology, Florida International University
2017	Edward and Rita Girden Cognitive Neuroscience Scholarship, from Florida International University
2014	Masters in Cognitive Sciences (Cognitive Psychology), Institute for Cognitive Sciences Studies, Tehran, Iran
2010	Bachelor of Arts in Psychology, University of Tehran, Tehran, Iran

PUBLICATIONS AND PRESENTATIONS

Pournaghdali, A. (2022). A multidimensional signal detection analysis of metacognitive sensitivity of prospective and retrospective metacognitive judgments. To be presented at The Southern Society for Philosophy and Psychology Annual Meeting, Mobile, Alabama. Invited Speaker

Pournaghdali, A., & Schwartz B. L. (2017). Signal detection analysis of non-conscious facial expression perception under continuous flash suppression. University of Miami Cognitive Studies Graduate Student Symposium, Miami, FL.

Pournaghdali, A., & Schwartz, B. L. (2017). Cognitive bias and conscious perception. The Southern Society for Philosophy and Psychology Annual Meeting, Savannah, GA.

Pournaghdali, A., & Schwartz, B. L. (2018). Conservative criterion explains the non-conscious perception of facial expression under continuous flash suppression. Vision Science Society Annual Meeting, St. Pete Beach, FL.

Pournaghdali, A., & Schwartz, B. L. (2020). Continuous flash suppression: Known and unknowns. *Psychonomic Bulletin & Review, 27,* 1071-1103.

Pournaghdali, A., & Schwartz, B. L. (2020). The Influence of emotional content on the tip of the tongue for the famous faces. The Southern Society for Philosophy and Psychology Annual Meeting. [Virtual]

Pournaghdali, A., Schwartz, B. L., Hays, J., & Soto, F. A. (In revision). Sensitivity vs. awareness curve: A novel model-based analysis to uncover the processes underlying nonconscious perception.

Pournaghdali, A., Schwartz, B.L., & Lee, H. (2020). The Influence of Valence on the Tip of the Tongue for the Famous Faces. Psychonomic Society Annual Meeting. [Virtual]

Pournaghdali, A., Schwartz, B.L., & Soto, F.A. (2020) Sensitivity vs. awareness curve: a novel model-based analysis to uncover the processes underlying nonconscious perception. The Object Perception, Attention, & Memory (OPAM) conference. [Virtual].

Pournaghdali, A., Schwartz, B.L., & Soto, F.A. (2020) Sensitivity vs. awareness curve: a novel model-based analysis to uncover the processes underlying nonconscious perception. The Annual Meeting of the Society for Mathematical Psychology. [Virtual]

Pournaghdali, A., Schwartz, B.L., & Soto, F.A. (2021). Investigating metacognitive sensitivity of tip-of-the-tongue states and feeling-of-knowing judgments with general recognition theory. Psychonomic Society Annual Meeting. [Virtual]

Pournaghdali, A., Schwartz, B.L., & Soto, F.A. (2021). Investigating metacognitive sensitivity of tip-of-the-tongue states and feeling-of-knowing judgments with general recognition theory. The Annual Meeting of the Society for Mathematical Psychology. [Virtual]

Schwartz, B. L., & Pournaghdali, A. (2016). Metacognition and conscious experience. *Behavioral and Brain Sciences, 39,* e195.

Schwartz, B. L., & Pournaghdali, A. (2020). Tip-of-the-tongue states: Past and future. In A. Cleary & B. L. Schwartz (Eds). Memory Quirks: The Study of Odd Phenomena in Memory (pp. 207-223). New York, NY: Routledge Press.

Schwartz, B. L., Pournaghdali, A., Hess, K. (Submitted). Comparative approaches to the natural ecology of metacognition.

Soto, F. A., & Pournaghdali, A., (2020). Sensitivity vs. awareness curve: a novel model-based analysis to uncover the processes underlying nonconscious perception. Vision Science Society Annual Meeting. [Virtual]