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Episodic Memory Precision and Reality Monitoring

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This dissertation is submitted for the degree of Doctor of Philosophy.

October 2020

Declaration

This thesis is a result of my own work, except for the following aspects of the thesis: some of the data collection for experiments reported in chapter 2 of the current thesis was assisted by Michael Siena, those reported in chapter 3 was assisted by Eddie Xiao, and those reported in chapter 4 was assisted by Ana Tew and Laura Woodrow.

This thesis is not substantially the same as any I have submitted, or is being submitted, for any other qualifications at the University of Cambridge or any other academic institution.

The total word count of this thesis does not exceed 60,000 words, adhering to the word limit prescribed by the Faculty of Biological Sciences Degree Committee at the University of Cambridge.

Acknowledgements

For providing an intellectually stimulating environment, I thank members of the memory lab, including Ali Trelle, Ayat Abdurahman, Carolin Sievers, Colleen Rollins, Franka Richter, Helena Gellersen, Jane Garrison, Michael Siena, Priya Jeyarathnarajah, Rose Cooper, and Saana Korkki. In particular, I would like to thank Jon Simons, who has taught the lab how to develop as scientists, supervisors, and most importantly, nice people.

I thank Amy Milton for both her tenacity to check in on my well-being and useful advises, the Adaptive Brain Lab for kindly sharing their transcranial magnetic stimulation facility, the Paul Bays Lab for answering any questions regarding memory precision modelling approaches, and Mihaela Taranu for teaching me the practical procedures of conducting experiments involving brain stimulations.

I thank the community of dancers at Cambridge, who have been essential for both by physical and psychological health. I have learned much dance moves from Anahita Talwar, Ann Yang, Hanna Tallinn, Mila Mundrova, Ronel Talker, Thomas Bignell, and Tim Yiu. In particular, I would like to thank Ezequiel Rodriguez and the Cambridge University Street Dance Team for being a constant source of joy for the community. It has also been a pleasure to serve the member of the Cambridge University Breakdancing Club and the Wolfson College Basketball Club.

I thank my father, Dae Eun Kwon, who has supported me especially during the toughest times along with Hyo Sook Ahn, Syra Kwon, and Ja Hoon.

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Abstract

The current thesis sought to investigate whether or not our ability to keep track of reality known as '*reality monitoring*' may depend on the qualitative characteristics of underlying mnemonic representations, such as the precision with which we remember details of past experiences (Johnson et al., 1993). To test this notion, experiments reported in the current thesis used behavioural measurements, brain stimulation, cognitive manipulations, and measures of individual differences. Data from these experiments, by and large, suggests that reality monitoring decisions may be associated with the precision of recollection, where greater reality monitoring performance tend to track greater precision of recollection. If, however, the precision of recollection is reduced, reality monitoring decisions may instead draw on a false sense of familiarity, as opposed to recollection, inducing a tendency to misattribute imagined experiences as those perceived from the outside world. Even people with, on average, greater precision of recollection tended to exhibit both behavioural and personality traits often observed in people with a tendency to lose touch with reality or 'psychosis', although this association did not survive stringent statistical corrections for false positive rates, suggesting that better mnemonic qualities may not always help us to keep track of reality. On balance, these findings suggest that multiple relationships may exist between reality monitoring decisions and the underlying mnemonic qualities. Such multiple relationships might be better described by a combination of previously separate theoretical accounts, rather than any single theoretical account. In light of these theoretical implications, the current thesis proposes a combined model that aims to account for the multiple relationships between qualities of mnemonic representation, reality monitoring decisions, and traits of psychosis.

Table of Contents

Chapter 1: General Introduction

Preview

Previous research on memory has revealed two types of long-term memory systems: '*episodic memory'*, which involves remembering personal experiences; and '*semantic memory'*, which concerns knowledge about facts and concepts (Tulving, 1972). Long-term memory can help us to recognise previously encountered information. This ability known as '*recognition memory*' consists of two separate retrieval processes: '*recollection*', which involves remembering contextual details of events, such as where and when an event happened; and '*familiarity*', which concerns a sense of knowing that an event happened, even when precise details of the event cannot be retrieved (Mandler, 1980; Tulving, 1985; Yonelinas, 2002). Recently, a growing amount of research has investigated the precision with which we recollect details of events, an ability known as '*episodic memory precision'* (Bays et al., 2009; Richter, Cooper et al., 2016). Episodic memory precision is considered to vary on a continuous scale, such that some mnemonic representations tend to be more veridical than others. To explain how we may keep track of veridical memory, a research framework known as the '*Source Monitoring Framework*' suggests that we monitor the original context or 'source' of memory (Johnson et al., 1993; Johnson & Raye, 1981). According to this framework, mnemonic representations may resemble different sources of information: '*internal sources*', including our own actions and imagined experiences; and '*external sources*', including actions performed by other people and perceptions of the outside world. Because of these resemblances, we may consider that a mnemonic representation originated from either internal or external sources. Such ability to distinguish internal and external sources of mnemonic representations is known as '*reality monitoring*'. Altogether, this PhD thesis aims to investigate whether or not reality monitoring decisions depend on qualitative characteristics of the underlying mnemonic representation, which can be captured by measuring episodic memory precision.

Episodic Memory Precision

According to seminal research on long-term memory, the ability to remember personal events requires three elements (Tulving, 1985, 1993, 2002). The first element is a person who can remember veridical details about personal events or the '*self'*. When we do remember an event, we may experience a sense of being mentally transported back to the event. This sense of mental time travel is the second element known as '*subjective time*'. While we mentally travel to a subjective time, we may become aware of the fact that we are remembering an event, rather than perceiving it. This sense of self-awareness is the third element known as '*autonoetic consciousness*'. Together, the self, a sense of subjective time, and autonoetic consciousness form a memory system that helps us to remember personal events that refers to '*episodic memory*'.

Episodic memory often involves remembering specific contexts of an event, such as where and when an event happened. Some researchers have argued that, if episodic memory is indeed contextually specific, episodic memory should be distinguishable from acontextual knowledge about facts and concepts, such as semantic memory. In support of this argument, for example, a neuropsychological study observed a double dissociation, where patients with Alzheimer's disease exhibit impaired episodic memory but relatively intact semantic memory; whereas patients with semantic dementia exhibit intact episodic memory but relatively impaired semantic memory (Nestor et al., 2006; Simons et al., 2002), suggesting that episodic and semantic memory might involve separate neuropsychological processes.

Even though neuropsychological experiments can tease apart episodic and semantic memory, it is important to acknowledge, however, that these memory systems often interact with each other (Greenberg & Verfaellie, 2010; Henson & Gagnepain, 2010). Episodic and semantic memory, for example, may help us to remember details of previously encountered event and feel that these information are familiar. This ability to recognise previously encountered information known as '*recognition memory*' is generally considered to consist of two separate retrieval processes: '*recollection*' and '*familiarity*'. According to the '*Dual Process Account*' (Mandler, 1980), recollection involves remembering contextual details of events, such as the name of a person that we have met before. In contrast, familiarity involves a sense of knowing that an event had occurred.

Research on recognition memory has investigated whether or not recollection and familiarity are distinct processes, developing seminal experimental paradigms. Notably, the 'Remember Know Paradigm' provided early evidence for a possible distinction between recollection and familiarity (Tulving, 1985). Research participants in this paradigm study a series of stimuli for a later retrieval phase, during which participants are presented with a mix of studied and new stimuli. Participants are asked to subjectively judge whether they either remember contextual details associated with each stimuli, such as where the stimuli was presented at encoding, or they know that the stimuli feels familiar but cannot recollect any contextual details. In this paradigm, ‘remember’ and ‘know’ responses may reflect recollection and familiarity, respectively. Accordingly, remember and know responses often exhibit distinguishable characteristics where, for example, remember responses tend to be more accurate than know responses (Yonelinas & Parks, 2007), suggesting that these responses may indeed reflect separate cognitive processes (Yonelinas, 2002). For instance, remember responses may reflect a more deliberate recollection of contextual details, inducing greater recognition accuracy; whereas know responses may reflect a relatively automatic feeling that a stimulus is familiar, without recollection, inducing relatively reduced recognition accuracy. A caveat of the Remember Know paradigm is, however, that participants may respond ‘remember’ even when they have not recollected contextual details or respond ‘know’ when they have recollected contextual details, but researchers cannot objectively check whether remember and know responses reflect recollection and familiarity, respectively.

To objectively distinguish recollection and familiarity, researchers have developed a different experimental paradigm, which measures the accuracy with which we recollect the context or the original ‘source’ of memory (Johnson et al., 1993). In the ‘*Source Monitoring Paradigm*’, participants study a series of stimuli from categorically different sources, such as objects presented at either the left or the right side of a computer screen. Researchers can check if participants both know that the object is familiar and remember the categorically correct location of each object. Participants’ categorically accurate source memory judgements may therefore reflect successful recollection, whereas inaccurate source memory judgements may only reflect a sense that an object is familiar. If accurate and inaccurate source memory judgments do indeed reflect recollection and familiarity, respectively, a double dissociation between these source memory judgements may be observable. A neuropsychological study observed such a double dissociation where, for example, patients with frontal lobe damage exhibited intact recognition but impaired source memory accuracy, whereas amnesiacs with little or no apparent frontal lobe dysfunction exhibit impaired recognition but intact source memory (Janowsky et al., 1989). This double dissociation suggests that the source memory paradigm may distinguish recollection and familiarity.

However, some researchers have argued that a distinction between recollection and familiarity is unnecessary, suggesting that this apparent distinction reflects two measurements of a single mnemonic process (Squire et al., 2007). According to the ‘*Single Process Account*’, the strength of memory varies on a continuous scale, ranging from stronger to weaker memory. Stronger memory may reach a threshold that signals accurate retrieval judgements, whereas weaker memory may not reach the threshold and therefore lead to inaccurate retrieval judgements. Therefore, a single process that detects mnemonic strength may result in categorically different retrieval judgements, such as remember and know responses, or accurate and inaccurate source memory judgements. According to this view, it is possible that both remember/know and source monitoring judgements reflect categorical measurements of a continuous mnemonic strength detection process, rather than two separate retrieval processes, such as recollection and familiarity.

In the last decade, there has been a growing appreciation among researchers focusing on memory retrieval that mnemonic qualities, including its strength, may indeed vary on a continuous scale. So we may recollect some extent of contextual details but importantly, recollection is still distinguishable from no retrieval at all (Onyper et al., 2010; Yonelinas et al., 2010). Evidence that we may recollect some-or-none of the contextual details of events stem from an experimental paradigm in the working memory literature known as the '*Precision Memory Paradigm*', which measures both the precision with which we recollect visuospatial details of an event, and whether we successfully retrieve visuospatial details or not (Bays et al., 2009a; Zhang & Luck, 2008). In adaptations of this paradigm for the study of long-term memory (e.g., Brady et al., 2013; Harlow & Yonelinas, 2016; Richter, Cooper et al., 2016), participants may study a series of objects located just outside a continuous circular space. Later during the retrieval phase, participants are presented with the objects that they have studied at a random location along the circular space. Participants are then asked to recreate the original location of the object from the study phase. This procedure often reveals errors between the original location and the participants' recreation of the original location, supporting the notion that we may recollect some extent of the original location with varying levels of precision. These errors are often normally distributed, where smaller errors are concentrated around the centre of the distribution, so a greater concentration of errors around the centre of the distribution reflects greater recollection precision. In contrast, participants sometimes cannot retrieve the original location at all and, therefore, participants may place the object at random locations around the circle, forming a uniform distribution that reflects random guesses. The area under the uniform distribution increases along with the number of guesses, so a higher uniform distribution reflects a greater proportion of random guesses relative to successful retrieval. Together, recollection precision and random guesses often result in two separate distributions of errors: a circular normal distribution known as the '*Von*

Mises distribution' and a '*uniform distribution*', respectively. A mixture model consisting of both distributions usually describe the errors better than either distribution on its own, corroborating the notion that we either recollect some extent of contextual details, or we fail to retrieve contextual details and, in turn, randomly guess.

Neurocognitive Basis of Episodic Memory Precision

Research on episodic memory precision sought to further investigate possible neurobiological distinctions between recollection precision and random guesses. Some of these studies have used a neuroimaging method known as '*functional magnetic resonance imaging*' (fMRI), which measures haemodynamic activity in the brain. These activations may correlate with mnemonic task performance, revealing possible neural correlates of memory. For example, a study by Richter, Cooper and colleagues (2016) measured participants' haemodynamic activity during the retrieval phase of a Precision Memory Paradigm. This study observed the angular gyrus to exhibit greater haemodynamic activity corresponding to greater recollection precision, suggesting that angular gyrus may facilitate recollection precision. In contrast, this study observed the hippocampus to exhibit greater haemodynamic activity corresponding to greater proportions of successful retrieval relative to random guesses, suggesting an association between hippocampus and retrieval success. Therefore, angular gyrus may facilitate recollection precision, whereas hippocampus may support retrieval success.

While a specific brain region, such as angular gyrus, may facilitate recollection precision, brain regions rarely work in isolation. When we engage in a cognitive function, multiple brain regions often activate together, and these brain regions that activate together tend to connect with each other, resulting in functional connections between regions that are involved in cognition (Hebb, 1949). Notably, an fMRI study observed that engaging in highly precise recollection usually increase functional connectivity between two regions: posterior parietal regions which include angular gyrus, and medial temporal regions which include hippocampus (Cooper & Ritchey, 2019). If this functional connection is involved in recollection precision, it is possible that enhancing this functional connection may enhance recollection precision. Accordingly, brain stimulation studies applied '*transcranial magnetic stimulation*' (TMS) to posterior parietal regions that exhibit functional connections to the hippocampus and observed the stimulation to enhance both the functional connection and recollection precision (Nilakantan et al., 2017; Tambini et al., 2018). Based on observations from both these fMRI and brain stimulation studies, some researchers have proposed that a brain network known as the ‘*posterior medial network*’ may facilitate precise recollection (Ritchey et al., 2015; Ritchey & Cooper, 2020).

If the posterior medial network does indeed facilitate precise recollection, disrupting parts of the network may impair precise recollection. Accordingly, a neuropsychological study investigated recollection precision in patients with medial temporal lobe resection and observed patients to exhibit relatively reduced recollection precision than healthy controls, suggesting that precise recollection may involve functioning of medial temporal regions (Nilakantan et al., 2018). This study also observed patients with resection in hippocampus to exhibit reduced recollection precision than patients without hippocampal resection, suggesting that precise recollection may specifically involve functioning of hippocampus. Another neuropsychological study has sought to investigate whether or not precise recollection involves subfields within the hippocampus (Stevenson et al., 2018). This study recorded intracranial electrophysiological activity in hippocampal subfields, and these recordings yielded two main findings: the specific hippocampal subfield ‘*Cornu Ammonis 1*’ (CA1) tends to exhibit activity corresponding to recollection precision, and this CA1 activity correlates with later activity in dorsolateral prefrontal cortex. Based on these findings, this study argued that CA1 may relay precise mnemonic information to dorsolateral prefrontal cortex for later mnemonic processes, such as post-recollection monitoring. However, it is important to note with caution that these neuropsychological studies recruited a small sample of patients (i.e., 3 patients with hippocampal resection and 4 patients with intracranial electrodes) and, therefore, neuropsychological evidence for medial temporal regions’ role in recollection precision may lack statistical power.

A statistically more robust evidence for medial temporal regions’ involvement in precise recollection has been observed in, for example, a study that measured temporal recollection precision, such as exactly when an event happened (Montchal et al., 2019). Participants in this temporal version of the Precision Memory Paradigm watch a series of video clips during the study phase. During the later retrieval phase, participants first view still-frames of clips from the study phase and in turn, participants indicate when this frame was presented on a continuous timeline, thereby providing a measure of temporal recollection precision. Measuring haemodynamic activity during the retrieval phase of this study revealed an association, where greater haemodynamic activity in medial temporal regions correspond to greater temporal recollection precision, suggesting that functioning of medial temporal lobe may be involved in precise temporal recollection (Montchal et al., 2019). Interestingly, however, this study also observed similar associations in regions outside of the medial temporal regions, including angular gyrus, retrosplenial cortex, precuneus, posterior cingulate cortex, and medial prefrontal cortex, suggesting that multiple regions may process temporally precise mnemonic information.

These regions associated with recollection precision, including both medial temporal and posterior parietal regions, are part of a wider brain network known as the '*recollection network*' (Johnson & Rugg, 2007; King et al., 2015; Rugg & Vilberg, 2013). Each region in this network may be associated with different aspects of precise episodic memory retrieval. In line with this view, seminal research on memory retrieval postulated that hippocampus, which resides in medial temporal lobe, may exhibit neural activities associated with remembering details of past events (Marr, 1971). Accordingly, comparative animal studies involving laboratory rats observed hippocampus to exhibit patterns of activity associated with complete details of past events, even when rats were presented with incomplete details (Leutgeb & Leutgeb, 2007; Marr, 1971; McClelland & Goddard, 1996). Based on such observations, these studies argued that hippocampus may engage in '*pattern completion*', which enables reconstruction of complete event details. Additionally, numerous neuroimaging and neuropsychological studies involving human participants implicate hippocampus in episodic imagery, which requires not only pattern completion but flexible recombination of event details (Bartlett, 1932; Hassabis & Maguire, 2007; Schacter et al., 2007). In contrast, posterior parietal regions have been often associated with manipulation of retrieved details in a temporary storage known as '*episodic buffer*' (Olson & Berryhill, 2009; Vilberg & Rugg, 2008). For example, posterior parietal regions may integrate multiple modalities of event details, so that we may generate a rich multimodal mental representation of past experiences (Bonnici et al., 2016; Ritchey & Cooper, 2020; Yazar et al., 2017). Damage to the posterior parietal region may therefore reduce a subjective sense of mentally reliving past experiences. In line with this view, neuropsychological studies involving patients with posterior parietal lesions observed, for example, patients to usually report reduced quality of autobiographical details than healthy controls (Berryhill et al., 2007; Davidson et al., 2008), and patients to also report reduced subjective confidence of recollection than healthy controls (Drowos et al., 2010; Simons et al., 2010). Altogether, precise episodic memory retrieval may involve multiple brain regions including medial temporal and posterior parietal regions, and each region may contribute different aspects of precise episodic memory retrieval, such as reconstruction, manipulation, and a subjective sense of reliving the past.

Importantly, none of these neurobiological processes involved in precise episodic memory retrieval are perfect. So some of our memories are more veridical, and some of our memories are false. In order to keep track of veridical memory, we may engage in post-recollection source monitoring (Johnson et al., 1993).

Reality Monitoring

According to seminal research on source memory, we recollect two types of information: '*internally-generated information*', which we derive from imagined experiences and our own actions; and '*externally-generated information*', which we derive from perception of the outside world or other peoples' actions (Johnson & Raye, 1981). Internally and externally generated information are often distinguishable by their characteristics, such as sensory, spatiotemporal, and semantic details. For example, a sense of having performed deliberate cognitive operations, such as creative or self-referential thinking, usually characterise internally generated information (Johnson et al., 1993). In contrast, perception is often more automatic than cognitive operations and, therefore, perception of externally generated information usually accompanies a weaker sense of having performed a cognitive operation (Johnson, 1988). So, instead of a sense of cognitive operation, rich perceptual details usually characterise externally-generated information. Because of these distinguishable mnemonic characteristics, we may come to expect that internally and externally generated information are qualitatively different. Therefore, we may consider whether a mnemonic representation resembles qualities often expected of internally or externally generated information, enabling the ability to distinguish internal and external sources of memory known as '*reality monitoring'*.

To investigate reality monitoring, two major types of reality monitoring tasks have been developed: '*agency reality monitoring*', which distinguishes actions performed by the self or another person; and '*perceptual reality monitoring*', which distinguishes imagined and perceived information (Simons et al., 2008b). In an agency reality monitoring task, for example, either the participant or the experimenter may read aloud commonly known word pairs, such as 'bacon and eggs' and 'Romeo and Juliet'. When a participant reads aloud a word pair, the participant is the agent that performed the action and, therefore, the participant may later retrieve a strong sense of having performed this action. Conversely, when an external agent such as the experimenter reads aloud a word pair, the participant may not feel such a sense of self-agency over the experimenter's action. Therefore, a strong sense of self-agency over participants' own actions may facilitate accurate agency reality monitoring decision. In contrast, participants in a perceptual reality monitoring task are asked to either imagine or perceive the second word of the word pair. Because perceived information usually comprises more perceptual details than imagined information, participants may accurately decide that a memory with rich perceptual details was in fact perceived information, resulting in accurate perceptual reality monitoring decisions.

Neurocognitive Basis of Reality Monitoring

Functional neuroimaging studies of reality monitoring have sought to investigate a possible neurocognitive basis of reality monitoring performance (Brandt et al., 2014; Kensinger & Schacter, 2006; Lagioia et al., 2011; Simons et al., 2006, 2008; Subramaniam et al., 2012; Turner et al., 2008; Vinogradov et al., 2008; Vinogradov et al., 2006). These studies reliably observed greater activity in medial prefrontal cortex corresponding to greater reality monitoring accuracy, suggesting that medial prefrontal cortex may support reality monitoring decision making processes. Conversely, studies involving schizophrenic patients observed patients to exhibit both reduced medial prefrontal activity and disrupted reality monitoring performance than healthy controls, suggesting that abnormally reduced medial prefrontal activity may be associated with reduced reality monitoring performance (Garrison, Fernandez-Egea, et al., 2017; Subramaniam et al., 2012; Vinogradov et al., 2008). Distinguishing different kinds of reality monitoring, a functional neuroimaging study directly compared neural correlates of agency and perceptual reality monitoring performance among healthy people (Simons et al., 2008). This study observed an anterior medial part of prefrontal cortex to exhibit greater activity corresponding to agency relative to perceptual reality monitoring performance, suggesting that agency and perceptual reality monitoring may involve separable neurocognitive processes. Altogether, these studies collectively suggest that medial prefrontal cortex may facilitate reality monitoring, and an anterior part of the medial prefrontal cortex may particularly facilitate agency reality monitoring.

To further investigate whether or not medial prefrontal cortex is necessary for reality monitoring, transcranial brain stimulation studies stimulated medial prefrontal cortex to observe a possible modulation of reality monitoring performance (Mammarella et al., 2017; Subramaniam et al., 2018; Moseley et al., 2018). One study observed stimulation of medial prefrontal cortex to reduce reality monitoring performance, but this observation was based on only 11 participants and, therefore, this observation may not generalise to a wider population (Subramaniam et al., 2020). Accordingly, a conceptually similar study did not replicate this observation (Moseley et al., 2018). Another conceptually similar study also did not replicate this observation among younger adults, although this study did report a rather specific replication using emotionally positive words among older adults without correction for multiple statistical comparisons (Mammarella et al., 2017). It is important to note, however, that brain stimulation may not always reach deep brain structures such as medial prefrontal cortex, so it may be limited in testing whether medial prefrontal cortex is necessary for reality monitoring decision making. Overall, a possible causal neurocognitive basis of reality monitoring remains elusive.

The Source Monitoring Framework

To explain how we may distinguish internal and external sources of memory, a research framework known as the '*Source Monitoring Framework*' was developed (Johnson & Raye, 1981). According to this framework, reality monitoring decisions depend, at least in part, on the underlying mnemonic quality, such as the precision of recollection, suggesting that reality monitoring performance may be associated with recollection precision. If, for example, recollection precision is tend to be greater, a clearer resemblance may emerge between mnemonic characteristics and qualities often expected of internal and external sources and, therefore, the respective reality monitoring accuracy may increase. Conversely, if recollection precision is reduced, reality monitoring accuracy may decrease. These postulations imply that mnemonic quality may be reduced in populations that exhibit reduced reality monitoring performance, such as patients with schizophrenia. In particular, studies involving schizophrenic patients with experience of hallucinations observed these patients to misattribute internally generated information to external sources, suggesting that mnemonic quality of internally generated information may be atypical, relative to externally generated information, especially among people who experience hallucinations (Bentall et al., 1991; Brébion et al., 2012; Mondino et al., 2019; Seal et al., 1997; Waters et al., 2006; Woodward et al., 2007). To interpret this finding, some studies have argued that patients' memory concerning internal sources of information, such their own actions, may be relatively imprecise and, therefore, involve less typical characteristics that distinguish them as self-generated (Bentall et al., 1991; Simons et al., 2017). Therefore, when patients are asked about their past actions, they may misattribute their actions to another person, thinking: 'I don't remember, it had to be you' (Johnson et al., 1993). One study compared reality monitoring performance between schizophrenic patients with experience of either multisensory or single-sensory hallucinations, and observed that patients with multisensory hallucinations are more likely to misattribute mental imagery to external sources (Mondino et al., 2019). This observation suggests that, when imagined experiences involve rich multisensory characteristics resembling qualities often expected of veridical memories, people with schizophrenia may misattribute mental imagery to an external source, thinking: ‘It’s so vivid, it had to be real’. Collectively, these tendencies to misattribute internally generated information to external sources are known as ‘*externalisation biases*’.

Sometimes, however, we cannot recollect any characteristic details and, therefore, reality monitoring decisions cannot always depend on recollection of mnemonic characteristics. So when recollection is unsuccessful, it is possible that reality monitoring decisions may depend on a memory system that does not require recollection. For example, we may retrieve knowledge about regularities across multiple events known as a ‘*schema*’ (Gilboa & Marlatte, 2017; Van Kesteren et al., 2012). Specifically, retrieval of a schema about internally and externally generated information may induce a feeling of knowing that a mnemonic trace originated from either internal or external sources. Accordingly, a theory that aims to explain differences between true and false memory known as the ‘*Fuzzy Trace Theory*’ postulates that we sometimes recollect imprecise memory or fuzzy mnemonic traces, so we may use schemas to internally generate a similar but ultimately false memory (Brainerd et al., 2008; Brainerd & Reyna, 1998). Accordingly, a hypothesis known as the ‘*guessing hypothesis*’ postulates that schemas may bias our decisions about the original sources of information (Bayen et al., 2000; Küppers & Bayen, 2014). If, for example, the strength of a schema about qualities of imagined experiences is weaker, we may experience a weaker sense of knowing that imagined information was in fact internally generated. Therefore, we may misattribute imagined information as perceived, resulting in an externalisation bias. Conversely, studies that investigated schemas across the lifespan suggest that, as we experience more events across the lifespan, schemas about these events becomes stronger and, coupled with age-related decline in recollection of specific details, we tend to more often falsely report having perceived events (Brod et al., 2013, 2017; Cohen & Faulkner, 1989; Dewhurst & Robinson, 2004; Lindsay et al., 1991; Markham, 1991; Markham et al., 1999; Mitchell et al., 2003; Sluzenski et al., 2004; Sussman, 2001). Altogether, both the Fuzzy Trace Theory and the guessing hypothesis postulate that schemas may contribute to the generation of a false memory, and we may misattribute these internally generated false memory as perceived.

More broadly, memory researchers generally agree that there are substantial individual differences in the quality with which people remember events from their pasts. So it is possible that, if reality monitoring decisions depend on mnemonic quality, people in the general population with, on average, reduced mnemonic quality may exhibit disrupted reality monitoring performance, resembling at least in part cognitive profiles often observed in patients with schizophrenia who experience of hallucinations (Simons et al., 2017). Interestingly, research on hallucinations in healthy people observed that some people who have no clinical diagnosis nevertheless report traits associated with psychosis, such as proneness to hallucinations and personality traits associated with schizophrenia known as '*schizotypy*' (Van Os et al., 2009). Based on such findings, a theoretical account of psychosis known as the '*psychosis continuum model*' postulates that individual differences in psychosis traits may vary on a continuum from clinical to healthy people, so some healthy people may indeed exhibit traits associated with psychosis (Meehl, 1962). According to this account, healthy people with more severe psychosis traits may exhibit cognitive profiles similar to schizophrenic patients, such as reduced reality monitoring performance. Inconsistent with this account, however, previous studies involving healthy people have not always observed a correspondence between psychosis traits and reality monitoring performance (Alderson-Day et al., 2019; Allen et al., 2006, 2006; Collignon et al., 2005; Garrison, Moseley, et al., 2017; Larøi et al., 2004). Therefore, evidence remains mixed for the notion that healthy people with greater psychosis traits may exhibit both reduced reality monitoring performance and reduced mnemonic quality.

Thesis Overview

The aim of this thesis is to test the key notion stemming from the Source Monitoring Framework, that reality monitoring decisions may depend on mnemonic quality. To test this postulation, experiments reported in chapters of the current thesis collectively investigate a possible association, where mnemonic quality predicts reality monitoring performance. Each chapter systematically investigated different aspects of this possible association, using a multidisciplinary approach that involves brain stimulation and cognitive manipulations. Chapter 2 investigated whether or not the precision with which people remember events was associated with their reality monitoring performance. Chapter 3 investigated whether retrieval of knowledge about mnemonic qualities often associated with either imagined or perceived experiences affected reality monitoring performance. Chapter 4 investigated whether the association between episodic memory precision and reality monitoring performance may be related to psychosis traits. Chapter 5 discusses the overall findings and their theoretical implications.

Experiments reported in Chapter 2 of the current thesis combined the Precision Memory Paradigm with reality monitoring tasks, to test whether greater recollection precision predicts greater reality monitoring performance. Behavioural experiments 2.1 and 2.2 did indeed reveal positive associations, where greater recollection precision tend to be associated with greater agency and perceptual reality monitoring performance, respectively. In experiment 2.1, recollection precision between self and other generated actions were comparable, but the association between recollection precision and reality monitoring performance tended to be stronger for self than other generated actions, suggesting that we may misattribute our own actions to another person, especially when recollection precision is reduced, resulting in an agency externalisation bias. In experiment 2.2, recollection precision of imagined events was usually reduced relative to perceived events, but the association between recollection precision and reality monitoring performance was comparable between imagined and perceived events, suggesting that we may misattribute unusually precise mental imagery as perceived, resulting in a perceptual externalisation bias. To investigate a possible causal neurocognitive basis of these associations, Experiments 2.3 and 2.4 applied brain stimulation at a region that has been associated with recollection precision, angular gyrus. Stimulating angular gyrus reduced the association between recollection precision and reality monitoring performance only for self-generated actions, suggesting that angular gyrus may be particularly necessary for our sense of self-agency. Altogether, findings in Chapter 2 support the key postulation of the Source monitoring framework, that reality monitoring decisions may be associated with mnemonic quality.

Experiments in Chapter 3 aimed to investigate whether or not retrieval of schemas induce externalisation biases, in instances where recollection precision is reduced. Experiment 3.1 tested whether presence, rather than absence, of schemas helps participants to learn the schemas. This experiment observed memory performance to be greater when schemas were present, relative to when schemas were absent, suggesting that participants do indeed learn schemas when it is present. To then test whether schemas may influence reality monitoring decisions, even when recollection is unsuccessful, Experiment 3.2 added a 24-hour delay between encoding and retrieval of stimuli. This experiment revealed the delay to selectively reduce episodic memory performance while preserving memory performance concerning schemas. To then investigate whether schemas induce externalisation bias, Experiment 3.3

tested whether the strength of schemas concerning perceived and imagined experiences tend to be associated with reality monitoring performance, and observed that a stronger schema concerning perceived relative to imagined experiences induce a perceptual externalisation bias. This finding is consistent with a postulation from both the Fuzzy Trace Theory and the guessing hypothesis, that retrieval of schemas may induce externalisation biases when recollection precision is reduced.

Experiments in Chapter 4 explored possible associations between each person's recollection precision and psychosis traits often associated with reduced reality monitoring performance. To this end, Experiment 4.1 measured recollection precision and two types of psychosis traits: proneness to hallucination (Waters et al., 2003) and schizotypy (Mason et al., 2005). This experiment did not yield any association despite the use of a large sample (n = 160), but it is important to note that participants' psychosis traits lacked variance and might have therefore obscured a possible association with recollection precision and psychosis traits. Experiment 4.2 therefore replaced traditional measures of psychosis traits with two novel measures validated with larger samples: the Cardiff Anomalous Perception Scale (Bell et al., 2006), and the Schizotypal Personality Questionnaire (Davidson et al., 2016). This experiment revealed people with greater memory precision to report greater schizotypy, although this result narrowly survived a correction for the likelihood of observing false positive results. This intriguing finding is inconsistent with a postulation of the psychosis continuum model, that reduced mnemonic quality may correlate with psychosis traits, often associated with reduced reality monitoring performance, among healthy people.

The order of experiments reported in Chapters 2 to 4 is logical, rather than chronological, so that experiments in Chapter 2 first report a possible relationship between each reality monitoring decision and the precision of recollection in the respective trial and, in turn, experiments in subsequent chapters gradually report more general relationships across multiple trials. This logical progression might have been obscured, if these experiments were reported in the chronological order: experiments reported in Chapter 4 were conducted first, followed by experiments in Chapters 2 and 3.

Chapter 5 discusses that multiple relationships observed between reality monitoring decisions and underlying mnemonic qualities may be better explained by a combination of previously separate theoretical accounts: the Source the Source Monitoring Framework (Johnson et al., 1993), the Fuzzy Trace Theory (Brainerd et al., 2008; Brainerd & Reyna, 1998), the guessing hypothesis (Bayen et al., 2000; Küppers & Bayen, 2014), and predictions regarding congruency and incongruency advantages (Greve et al., 2019; Sterzer et al., 2018; Van Kesteren et al., 2012). A single theoretical account, such as the psychosis continuum model (Meehl, 1962), may be insufficient to describe the multiple ways with which we may keep track of reality. In light of these theoretical implications, Chapter 5 proposes a combined model that aims to account for the multiple relationships between qualities of mnemonic representation, reality monitoring decisions, and traits of psychosis. Chapter 5 also discusses limitations of current experiments, such as challenges in establishing causal neurocognitive relationships between reality monitoring decisions and multiple mnemonic qualities. Future studies may improve upon such limitations to further investigate how reality monitoring decisions may interact with multiple mnemonic qualities.

Chapter 2: Episodic Memory Precision and Reality Monitoring

Introduction

Reality monitoring refers to our ability to keep track of whether our memories are veridical, as opposed to products of our imagination (Johnson & Raye, 1981). To explain how we may keep a grasp on reality, the Source Monitoring Framework proposes reality monitoring to involve considering the features of retrieved memories against characteristics expected of real and imaginary experiences. For example, memories full of vivid visuoperceptual detail may be more likely to be real than those primarily comprising internally generated thoughts. One prediction of this framework is that reality monitoring ability may depend on, at least in part, the precision with which we remember our actions and imaginings (Johnson et al., 1993; Johnson & Raye, 1981; Simons et al., 2017). If, for example, a memory is relatively vague and imprecise, we may struggle to distinguish whether it relates to an event that actually occurred, or one that we might have imagined. Traditional experiments on reality monitoring have tended to focus only on whether reality monitoring decisions are accurate or not, rather than the extent to which reality monitoring decisions may be affected by the quality of the underlying memories. Experiments in the current chapter aimed to bridge previously separate research relating to reality monitoring and memory precision, by asking the following research questions: does reality monitoring ability depend on the precision with which memories are retrieved? and what is the neurocognitive basis of this possible dependency?

The possible link between reality monitoring and memory precision has important implications for the understanding of symptoms of mental illness, such as hallucinations. It is possible that in schizophrenia, for example, patients' memories of their actions may lack precision, obscuring the self-referential characteristics that distinguish them as self-generated (Bentall et al., 1991; Seal et al., 1997; Waters et al., 2006; Woodward et al., 2007). Therefore, when patients are asked about their past actions, they may misattribute their actions to another person, thinking: 'I don't remember, it had to be you' (Johnson et al., 1981; Johnson & Raye, 1981). Conversely, when imagined experiences are unusually vivid or precise in detail, resembling qualities often expected of veridical memories, patients with schizophrenia may misattribute imagined experiences as real events, thinking: 'It's so vivid, it has to be real' (Mondino et al., 2019). Such resemblances may induce a tendency to misattribute internally generated information, such as our actions and imagined experiences, to those generated from external sources, such as actions performed by another person or perceptions of the outside world, a tendency known as an '*externalisation bias*'.

Investigating an externalisations bias and its underlying mnemonic qualities may help to understand cognitive profiles of some members of the healthy population known as 'nonclinical voice hearers', who report experiences of hallucinations without a diagnosis of psychiatric or neurological conditions (Baumeister et al., 2017). Non-clinical voice-hearers, for example, may share similar cognitive profiles with clinical populations with experience of hallucinations, such as externalisation biases and atypical qualities of mental experiences. Previous studies involving large samples of healthy people sought to investigate this notion, that externalisation biases may be associated with greater proneness to mental experiences with atypical qualities such as hallucinations. Some of these studies have observed a correspondence between externalisation biases and hallucination proneness (Allen et al., 2006; Collignon et al., 2005; Larøi et al., 2004), but other studies have not, however, observed such correspondence (Alderson-Day et al., 2019; Aynsworth et al., 2017; Garrison, et al., 2017). These studies suggest that even people who are highly prone to hallucinations may not exhibit externalisation biases. A caveat, however, is that participants in these studies made categorical 'yes' or 'no' responses to a series of statements about hallucinatory experiences, such as 'My thoughts seem as real as actual events in my life' (Launay & Slade, 1981). Such binary response options may have obscured qualitative differences in participants' experiences. Indeed, a study that asked clinical and non-clinical participants to provide categorical responses and also qualitatively describe their mental experiences found that, even when both groups responded 'yes' to a statement, different individuals described qualitatively dissimilar mental experiences (Stanghellini et al., 2012). Therefore, previous studies that used such categorical response measures may have been limited in measuring the variable qualities of mental experiences that may underlie externalisation biases.

To devise a more sensitive measure of mental experiences, the experiments in the current chapter combined reality monitoring tasks with a continuous response memory precision task adapted from the working memory literature (Bays et al., 2009). Richter, Cooper, and colleagues (2016) developed a long-term memory version of the memory precision task, asking their participants to study a series of displays consisting of objects overlaid at random locations around a circular space, and to later recreate the exact location of each object using a continuous response dial. A similar memory precision component was incorporated into the current study design to measure the precision of memories underlying two different reality monitoring decisions (Simons et al., 2008): agency reality monitoring decisions, which distinguish information generated internally by the self (i.e., the participant) and by an external agent (i.e., the experimenter); and perceptual reality monitoring decisions, which distinguish internally imagined and externally perceived information. The current experiment design bridges research in memory precision and reality monitoring, and is thereby able to test the extent to which different kinds of reality monitoring decisions may depend on the precision of underlying memories.

The second research question in the current chapter concerns the neurocognitive basis of this possible dependency between reality monitoring decisions and memory precision. If such a dependency exists, it implies a sequence of processes, in which the rememberer must first reconstruct a precise mnemonic representation and then decide its internal or external origin. This view suggests that brain regions associated with memory precision should typically be engaged before regions involved in reality monitoring decisions. In support of this neurocognitive sequence, time-sensitive electrophysiological studies have observed neural correlates of memory precision to occur at around 500-800ms post-stimulus-onset (Murray et al., 2015), whereas neural correlates of reality monitoring decisions may occur later, at around 1500-1800ms (Leynes & Kakadia, 2013). These neural data support the notion that precise recollection may occur earlier than reality monitoring decision making.

If reality monitoring decisions do indeed depend on memory precision, an experimental manipulation that reduces memory precision should induce worse reality monitoring performance. This hypothesis can be tested by disrupting the functioning of brain regions which exhibit hemodynamic responses that track memory precision, such as left angular gyrus (Richter & Cooper et al., 2016). Typical functioning of left angular gyrus may be disrupted by applying continuous theta burst stimulation (cTBS) (Huang et al., 2005). So applying cTBS at angular gyrus may disrupt memory precision and, in turn, reduce reality monitoring performance, compared with stimulation of a control site.

A further research question concerns the possible role of angular gyrus and neighbouring posterior parietal regions in processing internally generated first-person-perspective memories (Bonnici et al., 2018; Rugg & King, 2018; Weniger et al., 2009; Yazar et al., 2012, 2014, 2017; c.f. Drowos et al., 2010). If these regions process memories concerning internally generated information preferentially, stimulation of these regions may disrupt neurotypical functions associated with the internal ‘self’ and ‘imagined’ reality conditions more than the external ‘experimenter’ and ‘perceived’ reality conditions. This prediction would fit with a previous reality monitoring study which applied transcranial direct current stimulation over temporo-parietal junction, adjacent to angular gyrus, and observed a tendency to misattribute imagined verbal stimuli as externally perceived (Mondino et al., 2016). Therefore, stimulating angular gyrus with cTBS may disproportionately disrupt internal relative to external reality conditions, resulting in greater externalisation bias compared with control site stimulation.

In summary, experiments in Chapter 2 aimed to test two key questions stemming from the Source Monitoring Framework, that reality monitoring decisions may depend on the precision with which memories are retrieved, and that angular gyrus may represent a neurocognitive basis of this possible dependency. Experiments 2.1 and 2.2 investigated whether memory precision is associated with agency and perceptual reality monitoring performance, respectively. Experiments 2.3 and 2.4 investigated whether disrupting memory precision by applying cTBS at angular gyrus would lead to reduced reality monitoring performance. It was predicted that (1) variability in memory precision will have knock-on effects for reality monitoring performance, (2) cTBS at angular gyrus will disrupt memory precision and, in turn, reduce reality monitoring performance, and (3) angular gyrus cTBS will disproportionately disrupt retrieval of internally relative to externally generated information, resulting in externalisation biases.

Method

Participants

Forty-eight participants between 18 to 35 years of age were included in each experiment. All participants took part in only one of the four experiments in the current chapter (N = 192). All participants reported normal or corrected-to-normal vision and hearing, and no history of psychiatric or neurological conditions. Participants provided informed consent in accordance with the procedure approved by the University of Cambridge Human Biology Research Ethics Committee.

Four additional participants withdrew: one reported discomfort after administration of a single motor threshold pulse, one reported nausea after four motor threshold pulses, one reported discomfort after about 10s of cTBS, and one reported pain 5 minutes after (but not during) the cTBS. Sessions were terminated immediately when participants reported any discomfort, nausea, or pain. No participants reported subsequent side effects. One volunteer withdrew, explaining that they could not follow the instructions for the ‘imagined’ reality condition in Experiment 2.3 due to self-reported aphantasia, which often involves an inability to imagine visuospatial information (Zeman et al., 2015).

Stimuli

Each display consisted of an image of a real-world object overlaid on a faint patterned background. The images were obtained from Google image searches and a real world object stimuli bank from Brady and colleagues (2008) (https://bradylab.ucsd.edu/stimuli.html). A total of 360 displays were used.

The following variables were randomly allocated between participants: the pairing of objects with backgrounds, object target locations around a circular space between 1-360°, displays in each reality condition (i.e., 'self', 'experimenter', 'imagined', and 'perceived'), stimulation site (i.e., angular gyrus and vertex), and display presentation order within each study-test cycle. The displays were identical between participants, but the display presentation order was different for each participant.

Procedures

Across Experiments 2.1 to 2.4, I tested all participants in person. In behavioural experiments 2.1 and 2.2, I was present in the testing room at all times. In brain stimulation experiments 2.3 and 2.4, at least one additional experimenter was within hearing distance of the testing room, in accordance with both the first aid training (provided by St John's Ambulance) and the brain stimulation safety guideline (Rossi et al., 2009).

Stimuli were presented on a computer screen, using a programming functions package 'Psychtoolbox' (versions 3.0.13 and 3.0.14) and a programming software 'Matlab' (versions 2017b and 2018b). Different versions of either Psychtoolbox or Matlab did not affect the presentation of the stimuli.

Experiment 2.1: Agency Reality Monitoring

Participants were asked to complete a practice task followed by 7 study-test cycles. Each cycle consisted of 24 displays, half of which were in the 'self' condition, and the other half were in the 'experimenter' condition.

In each study phase trial, we presented a cue (lasting 1s), which indicated whether the self (i.e., the participant) or the experimenter was to move the object that was subsequently presented in the middle of the computer screen. In the 'self' condition, participants were asked to hold down the spacebar on a keyboard to move the object progressively to its target location, whereas in the 'experimenter' condition, participants were asked to watch the object move progressively to its target location as the experimenter held down the 'Q' key (within 3s of the object being presented). When the object reached its target location, participants were asked to think about what the object was, where its target location was, and whether they themselves or the experimenter moved the object (3s).

In each test phase trial, we presented a studied object at a random location around a circular space. Participants were asked to first recreate the target location of each object by holding down the left and right arrow keys, which moved the object anti-clockwise and clockwise around the circular space, respectively. Participants were also asked to decide whether the object had been moved by the participant themselves or the experimenter during the preceding study phase by pressing the 'S' and 'E' keys, respectively. The trials were subject paced, terminating if participants did not respond after 9s. We presented a text reminder of what each key represented in the middle of the computer screen, which turned red to indicate when 3s was left before the trial expired.

Experiment 2.2: Perceptual Reality Monitoring

Participants were asked to complete a practice task followed by 10 study-test cycles. Each cycle consisted of 18 displays, half of which were in the 'imagined' condition, and the other half were in the 'perceived' condition. We used fewer displays for each study-test cycle in experiment 2 (i.e., 18 displays) relative to experiment 1 (i.e., 24 displays) to prevent floor effects that emerged in pilot testing of this experiment.

In each study phase trial, we presented an object in the centre of the computer screen (3s). In the 'imagined' condition, the object was replaced by a black cross, and participants were asked to imagine the object moving progressively to the target location as the cross moved progressively to the target location (1s). In the 'perceived' condition, participants were asked to watch the object move progressively to its target location (1s). When the cross or the object reached its target location, participants were asked to think about what the object was, where its target location was, and whether the movement of the object was imagined or perceived (3s).

The test phase of experiment 2 was identical to the test phase of experiment 1, except that participants were asked to press the 'I' and 'P' keys to indicate whether the object had been imagined or perceived during the preceding study phase, respectively. See Figure 2.1 for an overview of the procedures of Experiments 2.1 and 2.2.

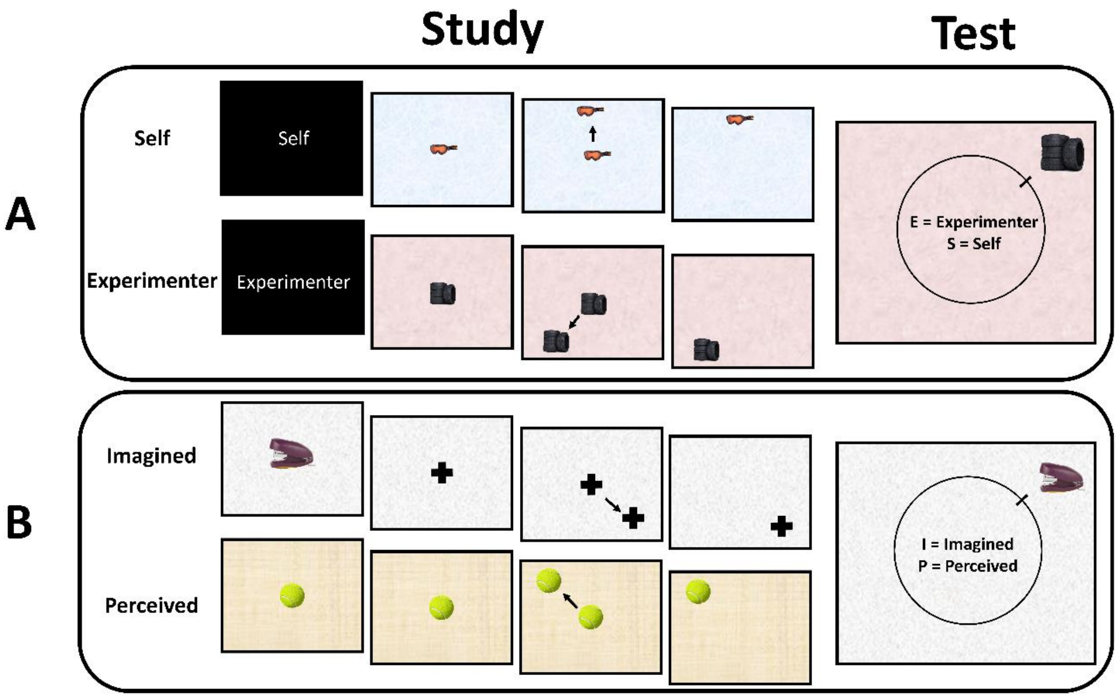

Figure 2.1. Reality Monitoring Tasks. In the agency reality monitoring task (A), participants were first presented with a cue indicating whether the participant or the experimenter was to move the following object (1s). Then, participants were asked to either moved the object progressively from the centre of the screen to its target location (a random location around a circle), or they watched the experimenter move the object to its target location (3s). Participants were then asked to recreate the target location and indicate whether the self or the experimenter had moved the object (9s). In the perceptual reality monitoring task (B), participants were first presented an object at the centre of the screen (3s). In the 'imagined' reality condition, the object was replaced by a black cross, and participants were asked to imagine the object moving progressively to the target location as the black cross progressively moved to the target location; whereas in the 'perceived' reality condition, participants were asked to watch the object move progressively to its target location (1s). Participants were then asked to recreate the object location and indicate whether the movement of the object had been imagined or perceived (9s).

Experiments 2.3 and 2.4: Brain Stimulation

The procedures for Experiments 2.3 and 2.4 were identical to Experiments 2.1 and 2.2, respectively, except that cTBS was applied to either the control stimulation site (vertex) or angular gyrus just before the beginning of the first study phase. The order of stimulation site was counterbalanced across two sessions, which took place on separate days (see below). Different object stimuli were used in each session.

Both Experiments 2.3 and 2.4 sought to control for the possibility that cTBS at angular gyrus might disrupt object perception or recognition, as well as memory performance. A failure to perceive or recognise studied objects could confound our measure of memory precision. To address this possible confound, we asked participants also to perform a control semantic task, in which participants had to successfully perceive and recognise each object in order to accurately decide whether the object could fit inside a shoebox or not. At the end of each study trial, participants were asked to indicate 'yes' and 'no' by pressing 'Y' and 'N' keys, respectively (within 3s or until a response was made). Participants' performance on this semantic task was compared between reality conditions and stimulation sites, to test whether these conditions might have affected participants' ability to perceive and recognise objects (see 'Control Semantic Task Performance' section below for the results).

Brain Stimulation

The control brain stimulation site was the probabilistic anatomical vertex (MNI (Montreal Neurological Institute) coordinates: 0, -15, 74) (Okamoto et al., 2004). The experimental stimulation site was the average peak hemodynamic correlate of memory precision at left angular gyrus (MNI coordinates: -54, -54, 33) (Richter, Cooper, et al., 2016). To identify these stimulation sites on each participant's scalp, half of the participants were registered to their respective T1-weighted structural magnetic resonance head scan, whereas the other half of the participants, for whom no structural scan was available, were registered to the average MNI template head scan provided by Brainsight 2.3.3. The registration method made no significant difference to the results. See Figure 2.2 for an illustration of these brain stimulation site.

The Magstim Rapid 2 stimulator connected to a non-invasive 70mm figure-of-eight coil was used to induce electrical currents in participants' brains. The resting motor threshold of each participant was estimated via the TMS Motor Threshold Assessment Tool 2.0 (https://www.clinicalresearcher.org/software.htm), which uses a maximum-likelihood strategy to identify the minimum intensity required to elicit a motor response in each participant's right index finger or thumb. Participants who did not show any motor response were administered the default resting motor threshold, which is 70% of the maximum stimulator output. The stimulation intensity for each participant was calculated as 70% of their resting motor threshold which, in accordance with safety guidelines (Rossi et al., 2009), did not exceed 49% of the maximum stimulator output. To prevent the effect of stimulation accumulating, the stimulation sessions were separated by at least 48 hours. To schedule practically, the delay between stimulation sessions was limited to one week. The distance between the target stimulation site and the centre of the coil did not exceed 2mm during the 40s cTBS for all participants in both Experiments 2.3 and 2.4. See Figure 2.2 for an illustration of delivering a single electromagnetic pulse to the target brain stimulation sites.

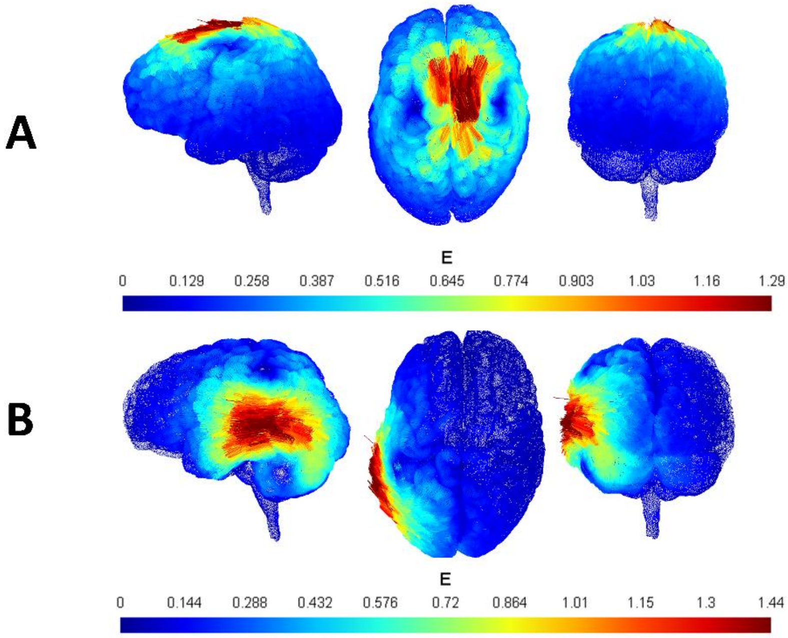

Figure 2.2. Brain Stimulation Sites. Paricipants in Experiments 2.3 and 2.4 received brain stimulation at the control stimulation site vertex (MNI: 0, -15, 74) (A) and angular gyrus (MNI: -54, -54, 33) (B). Stimulation of each site was separated into two sessions on different days, and the order of stimulation site was counterbalanced. The colours in the figure represent a simulated electric field ‘E’. The simulations assume using a 70mm figure-8-coil to deliver a single electromagnetic pulse to a template brain in SimNIBS.

Analysis Approach

All experiments in the current chapter excluded trials with less than 0.5s reaction time or no responses (a total of 852 trials were excluded out of 33,408 trials, or 0.256% of all trials). Reality monitoring accuracy was measured on a binary scale: ‘1’ for correct and ‘0’ for incorrect responses. To estimate memory precision, the target location angle was subtracted from the participants’ recreation of the target location angle, resulting in angular error (in degrees). The angular error was then subtracted from the maximum possible error (i.e., 180º), so that greater values represented greater memory precision. To prevent unsuccessful recollection or ‘random guesses’ from confounding the estimate of memory precision, trials with less than or equal to 5% likelihood of originating from successful recollection was excluded (see Bays et al., 2009; Richter, Cooper et al., 2016; Schneegans & Bays, 2016). The statistical package ‘lme4’ in R might have taken a long period of time to estimate the best fit between a regression model and the observed data, if the scales of variables were irregular (Bates et al., 2015). To prevent irregularities in the scales of memory precision and other variables, such as reality monitoring accuracy, reality condition, and stimulation site, memory precision was scaled using the ‘scale’ function in the ‘standardize’ package in R, which divided each observation by the root mean square across observation. This scaling procedure yielded, across all Experiments 2.1 to 2.4 in the current Chapter 2, minimum and maximum memory precision values of ‘0’ and ‘1.099’, respectively, suggesting that this scaled measure of memory precision may be more comparable to binary dependent variable, relative to the unscaled measure of memory precision.

Across all experiments reported in the current chapter 2, two levels of analyses were conducted: random effects analysis, which may reveal a possible item-level association where a reality monitoring decision concerning an item, such as a spoon, may be associated with the precision with which the location of the respective item was retrieved, rather than memory precision concerning any other item (e.g., a book, lamp, chair, etc.); and the fixed effects analysis, which may reveal across-item level association where, on average, reality monitoring decisions may be associated with memory precision.

In the random effects analysis, therefore, reality monitoring accuracy concerning an item or ‘reality monitoring accuracy_i’ may be associated with ‘memory precision_i’. This possible random effects association may vary between participants or ‘j’. Taken together, this item-level association may be formalised by the following random effects regression model equation: ‘Reality Monitoring Accuracy_{ij} = β*Memory Precision_{ij} + Constant + Error’, where ‘i’ represents the ith item and ‘j’ represents the jth participant. This random effects regression model may yield a regression coefficient for each participant, where the intercept, slope and direction of the coefficient may vary between participants.

Whereas in the fixed effects analysis, reality monitoring performance across items or ‘average reality monitoring accuracy’ may be associated with ‘average memory precision’. This across-item level association may be formalised by the following equation: ‘Average Reality Monitoring Accuracy_j = β*Average Memory Precision_j + Constant + Error’, where ‘j’ represents the jth participant'. This fixed effects regression model may yield a regression coefficient which characterise an across-item level association between reality monitoring performance and memory precision.

Both random and fixed effects analyses were conducted together, by computing mixed effects regression models. In behavioural Experiments 2.1 and 2.2, the mixed effects model included the 'reality monitoring conditions' predictor. This mixed effects model may, therefore, reveal both item-level and across-item level associations, between reality monitoring performance and memory precision, to be different between reality monitoring conditions. Mixed effects regression models in brain stimulation Experiments 2.3 and 2.4 additionally included the 'stimulation site' predictor. This mixed effects model may reveal, for example, stimulation of angular gyrus to significantly reduce the behavioural associations, relative to the control site stimulation.

Parameters of the model were selected using two approaches: the 'backward' approach first included all parameters in the model and, in turn, removed one parameter from the model at each step; whereas the 'forward' approach first included only one parameter in the model and, in turn, added another parameter to the model at each step.

Both model selection approaches yielded a runtime error, at least in part, because the computer took too long a period of time to compute the models (rather than misspecification of the model parameters or lack of data). To inspect how much runtime might have been required to converge these models, it is often useful to first estimate the runtime for simpler models with fewer parameters that did converge and, in turn, estimate how much additional runtime might have been sufficient to converge relatively more complex mixed effects models. Simpler models which included just one mixed effects parameter, concerning memory precision, converged within 6 minutes; whereas models that additionally included the 'reality monitoring condition' parameter did not converge. A possible reason for this runtime error is that the estimated runtime to converge these models might have exceeded the maximum runtime allowed to converge these models or the 'runtime guard'.

Follow-up inspection sought to estimate by how much the runtime guard should be raised, so that these models including the additional 'reality monitoring conditions' parameter may converge. A possible approach was to first converge the model with just one participant's data, selected randomly, and then multiply this single-participant runtime by the total number of participants in each experiment (i.e, 48 participants), yielding a possible total runtime to converge the model with all participants' data. The single-participant runtime was 5 hours, suggesting that runtime to converge the model across all 48 participants may be at least 240 hours (or 10 days). Computing the model with 48 participants' data did not converge even after 14 days, however, partly because of two following reasons: the processing speed of the computer tended to decrease as the duration of runtime increased, and including a parameter concerning a possible interaction effect tended to increase the total runtime exponentially, rather than linearly. Regression models further including the 'brain stimulation' parameter did not converge even after 30 days, suggesting that including all parameters in one complicated mixed effects model may be practically challenging and, therefore, less amenable to validations and replications.

To reduce the runtime and thereby increase the likelihood of model convergence, the random and fixed effects analyses were conducted separately, yielding both item-level and across-item level analyses. These multiple levels of analyses may collectively form the multi-level analysis, which is sometimes referred to as the 'multiverse analysis' (Steegen et al., 2016).

If reality monitoring accuracy concerning internal reality monitoring conditions (i.e., 'self' and 'imagined' conditions) tend to be disproportionately lower, relative to the external condition (i.e., the 'Experimenter' and 'perceived' conditions), this tendency to misattribute internally generated memories to external sources may reflect a response bias known as the 'externalisation bias'. The extent of externalisation bias was, therefore, estimated as the relative reality monitoring accuracy concerning internal and external reality monitoring conditions. If externalisation bias tend to be associated with disproportionately lower memory precision concerning internal reality monitoring conditions, relative to external conditions, externalisation bias may be associated with memory precision, although externalisation bias and memory precision may reflect a response bias and memory sensitivity, respectively. Excluding random guess trials varied the amount of data between reality conditions, stimulation sites conditions, and participants, potentially confounding within-subject level analysis. To enable within-subject random effects analyses, the amount of data in each condition was equated by randomly sampling, with replacements, trials with more than 95% likelihood of successful recollection. The number of sampled data were the maximum number of trials in each reality condition: 84 for each agency reality condition, and 90 in each perceptual reality condition. To reduce resampling bias, all analyses were permutated in increments of 100 permutations, until the average standard error of all analysis outputs across resampling approached 0. The average permutated regression model outputs, including generalised eta squared values, are reported in the results section below.

One of the assumptions of conducting these regression models is linearity between log of the outcome variable (i.e., reality monitoring accuracy) and the predictor (i.e., memory precision). This assumption was checked by visually inspecting scatter plots between the log outcome variable and the predictor, revealing that that the linearity assumption was satisfied. Another assumption concerned potential outliers, where a small number of influential observations might have biased the main statistical results. Potential outliers were identified by first estimating Cook's Distance of each observation and, if the Cook's Distance was greater than 1, the observation was labelled as an outlier. This outlier detection approach did not reveal any outliers.

To estimate the statistical power with which Experiments in Chapter 2 might observe a significant effect, power analyses were conducted for following regression models: a model where the outcome variable (i.e., reality monitoring accuracy) was predicted by two predictors (i.e., memory precision and reality monitoring conditions) in behavioural Experiments 2.1 and 2.2; and a similar model with an additional predictor (i.e., stimulation site) in brain stimulation Experiments 2.3 and 2.4. These power analyses revealed that, to detect a medium size effect, 32 participants were needed in each behavioural experiment; whereas 37 participants were needed in each brain stimulation experiment (f = 0.25, α = 0.05, $1\text{-}\beta$ = 0.8). To counter-balance the order of stimulation site, however, 48 participants were needed in each brain experiment and, to ensure that the main statistical analyses were comparable across behavioural and brain stimulation experiments in Chapter 2, the number of participants were matched across all experiments (f = 0.25, α = 0.05, $1\text{-}\beta$ = 0.952). These power analyses were conducted in R, using the 'pwr.f2.test' function in the 'pwr' package.

The main analyses in the current chapter were conducted in 'R', using multiple statistical functions and packages: both repeated measures and mixed ANOVAs were conducted using the 'ezANOVA' function in the 'ez' package; logistic regressions were conducted using the 'glmer' function in the 'lme4' package; repeated measures t-tests were conducted using the 't.test' function, which is a base function built into R.

Results

Externalisation Biases are Associated With Reduced Memory Precision

Analyses in Experiments 2.1 and 2.2 first sought to test whether participants' reality monitoring performance tended to be lower in the internal than external reality conditions, which would correspond to an externalisation bias. Repeated measures ANOVAs testing for an effect of reality condition on reality monitoring accuracy revealed significant effects in both Experiment 2.1 ($F(1,47) = 39.749$, $ges = 0.02$, $p < 0.001$) and Experiment 2.2 ($F(1,47) = 12.738$, $ges = 0.087$, $p = 0.001$). In both experiments, reality monitoring accuracy was lower in the internal than external reality conditions, consistent with externalisation biases (see Table 2.1 for descriptive statistics).

To assess whether these externalisation biases might be linked to reduced memory precision, subsequent analyses tested whether memory precision was lower in the internal relative to the external reality conditions. Repeated measures ANOVAs testing for an effect of reality condition on memory precision did not find an effect in Experiment 2.1 ($F(1,47) = 0.884$, $ges = 0.001$, $p = 0.417$) but did reveal a significant effect in Experiment 2.2 ($F(1,47) = 19.593$, $ges = 0.008$, $p < 0.001$), in which memory precision was lower in the imagined relative to perceived reality condition.

Table 2.1. Mean (SE) reality monitoring accuracy (%) and memory precision in each reality condition in all Experiments 2.1 to 2.4.

	Experiment 2.1		Experiment 2.2		Experiment 2.3		Experiment 2.4	
	Self	**Experimenter**	**Imagined**	**Perceived**	**Self**	**Experimenter**	**Imagined**	**Perceived**
Reality Monitoring Accuracy (SE)	74.976 (2.363)	88.776 (1.365)	77.274 (2.452)	86.048 (1.427)	79.501 (5.827)	88.479 (4.609)	71.868 (6.491	85.208 (5.125)
Mean Memory Precision (SE)	140.347 (7.087)	140.228 (6.968)	129.595 (7.623)	139.162 (7.141)	166.456 (1.934)	166.602 (1.851)	162.898 (2.212)	165.129 (2.042)

Table 2.2. Mean (SE) Control Semantic Task Accuracy (%) in Experiments 2.3 and 2.4.

	Experiment 2.3				Experiment 2.4			
	Self		Experimenter		Imagined		Perceived	
	AnG	**Vertex**	**AnG**	**Vertex**	**AnG**	**Vertex**	**AnG**	**Vertex**
Control Semantic Task Accuracy	96.968	97.068	97.021	96.518	95.198	95.446	95.423	95.614
(SE)	0.266	0.377	0.311	0.305	0.373	0.412	0.402	0.34

Note. The term ‘AnG’ refers to the target brain stimulation site, angular gyrus.

I then sought to test whether the association between reality monitoring accuracy and memory precision differed between the internal relative to the external reality conditions. These associations were estimated via separate mixed effects logistic regressions in each reality monitoring condition, where the outcome variable was reality monitoring accuracy, the predictor was memory precision, , and the random effects variable was 'participants'. This model was formalised as the following equation: '*Reality Monitoring Accuracy*$_{ij}$ = β**Memory Precision*$_{ij}$ + *Constant* + *Error*', where the 'β' represents the regression coefficient and the 'i' represents the ith participant and 'j' represents jth reality monitoring condition. Separate logistic regressions in each reality condition revealed significant positive associations in all reality conditions (β >= 2.731, R^2 >= 0.304, *p* <= 0.014), except for the 'experimenter' reality condition in the agency reality monitoring task (β = 1.924, R^2 = 0.323, *p* = 0.268). This association, or regression coefficients, between reality monitoring accuracy and memory precision was the dependent variable in repeated measures ANOVAs testing for an effect of reality condition on these associations, which revealed significant effects in both Experiment 2.1 (*F*(1,47) = 9.685, *ges* = 0.121, *p* = 0.003) and Experiment 2.2 (*F*(1,47) = 5.479, *ges* = 0.054, *p* = 0.024). In Experiment 2.1, the association in the internal 'self' reality condition was stronger (*M* = 4.363, *SE* = 0.511) than in the external 'experimenter' reality condition (*M* = 1.906, *SE* = 0.419); whereas in Experiment 2.2, the association in the internal 'imagined' reality condition was smaller in magnitude (*M* = 2.771, *SE* = 0.437) than in the external 'perceived' reality condition (*M* = 4.25, *SE* = 0.444).

A mixed ANOVA testing the effects observed in Experiments 2.1 and 2.2 revealed a significant cross-over interaction between reality condition (internal vs external) and experiment (*F*(3,141) = 6.102, *ges* = 0.094, *p* = 0.006).

Control Semantic Task Performance

Turning to Experiments 2.3 and 2.4, the first set of analyses aimed to test whether reality condition and stimulation site affected participants' accuracy on the control semantic task, which might reflect their ability to successfully perceived and recognise objects. In both Experiments 2.3 and 2.4, ANOVAs comparing participants' accuracy on the control semantic task between reality conditions and stimulation sites did not reveal any significant effect of reality condition (*F*(1,47) <= 0.947, *ges* <= 0.003, *p* >= 0.335) or stimulation site (*F*(1,47) <= 0.448, *ges* <= 0.002, *p* >= 0.507). No significant interaction was observed between reality condition and stimulation site (*F*(1,47) <= 1.04, *ges* <= 0.004, *p* >= 0.313; see Table 2.2 for descriptive statistics).

Stimulating Angular Gyrus Did Not Reduce Reality Monitoring Performance or Memory Precision

The main analyses aimed to test whether cTBS at angular gyrus was associated with main effects of reduced memory precision or reduced reality monitoring performance. Repeated-measures ANOVAs did not reveal a significant main effect of stimulation site on memory precision ($F(1,47) <= 0.79$, $ges <= 0.004$, $p >= 0.438$) or reality monitoring accuracy ($F(1,47) <= 0.266$, $ges <= 0.001$, $p >= 0.658$).

I then sought to test an a-priori prediction, that cTBS at angular gyrus might selectively reduce memory precision in the internal relative to external reality conditions. Repeated measures ANOVAs testing whether an interaction between stimulation site and reality condition affected memory precision, however, did not reveal an interaction effect on memory precision ($F(1,47) <= 0.356$, $ges <= 0.001$, $p >= 0.439$).

Stimulating Angular Gyrus Reduced the Association Between Reality Monitoring Accuracy and Memory Precision

Further analyses tested whether cTBS at angular gyrus disrupted the positive associations observed between reality monitoring accuracy and memory precision. The associations were first estimated by first computing separate mixed effects regression models in each stimulation site, where the outcome variable was reality monitoring accuracy, predictor was memory precision, and random effects variable was ‘participants’. This model was formalised as the following equation: ‘$Reality\ Monitoring\ Accuracy_{ijkl} = \beta * Memory\ Precision_{ijk} + Constant + Error$’, where the ‘$_i$’ represents the ith participant, ‘j’ represents the jth participant, ‘k’ represents kth reality monitoring condition, and ‘l’ represents lth stimulation site. Following repeated measures ANOVAs testing for an effect of stimulation site on the association (i.e., regression coefficients) between reality monitoring accuracy and memory precision did not reveal a significant effect ($F(1,47) <= 1.292$, $ges <= 0.001$, $p >= 0.081$).

Follow-up analysis sought to test an a-priori prediction, that cTBS at angular gyrus might selectively reduce the association between reality monitoring accuracy and memory precision in the internal relative to external reality conditions. The associations were first estimated by first computing separate mixed effects regression models in each reality monitoring condition within each stimulation site. Following repeated measures ANOVAs testing whether an interaction between stimulation sites and reality conditions affected these associations revealed a significant interaction in the agency reality monitoring task ($F(1,47) = 14.455$, *ges*

= 0.068, $p < 0.001$) but not in the perceptual reality monitoring task ($F(1,47) = 1.951$, *ges* = 0.007, $p = 0.169$). Follow-up pair-wise comparisons in the agency reality monitoring task revealed that cTBS at angular gyrus significantly reduced the association in the 'self' reality condition ($t(1,47) = 4.252$, $d = 0.868$, $p < 0.001$) but not in the 'experimenter' reality condition ($t(1,47) = 1.357$, $d = 0.311$, $p = 0.18$).

A post hoc mixed ANOVA directly comparing the effects observed in agency and perceptual reality monitoring tasks revealed a significant three-way interaction between reality condition, stimulation site, and experiment ($F(1,94) = 4.328$, *ges* = 0.01, $p = 0.04$). See Figure 2.3 for an illustration of this three-way interaction. This post hoc comparison might have, however, increased the likelihood of observing a false positive result and, therefore, this likelihood was adjusted by applying the Bonferroni multiple comparisons correction (corrected alpha = 0.025). This correction did not reveal a statistically significant three-way interaction. Another note of caution concerns the allocation of participants to either one of the experiments: if participants signed up for a specific experiment, they were allocated to the respective experiment; whereas if they signed up to participate in either one of the experiments, they were allocated to either experiment in an alternate order. This pseudo-random allocation of participants might have introduced a possible order effect. To test this possible order effect, Levene's test for homogeneity of variance was conducted, where the outcome variable was the association between reality monitoring accuracy and memory precision, and the predictor was Experiment. This homogeneity test, across all conditions (i.e., reality monitoring condition and stimulation site), did not reveal a significant difference in variances between Experiments 2.3 and 2.4 ($F(1,382) = 0.646$, $p = 0.42$).

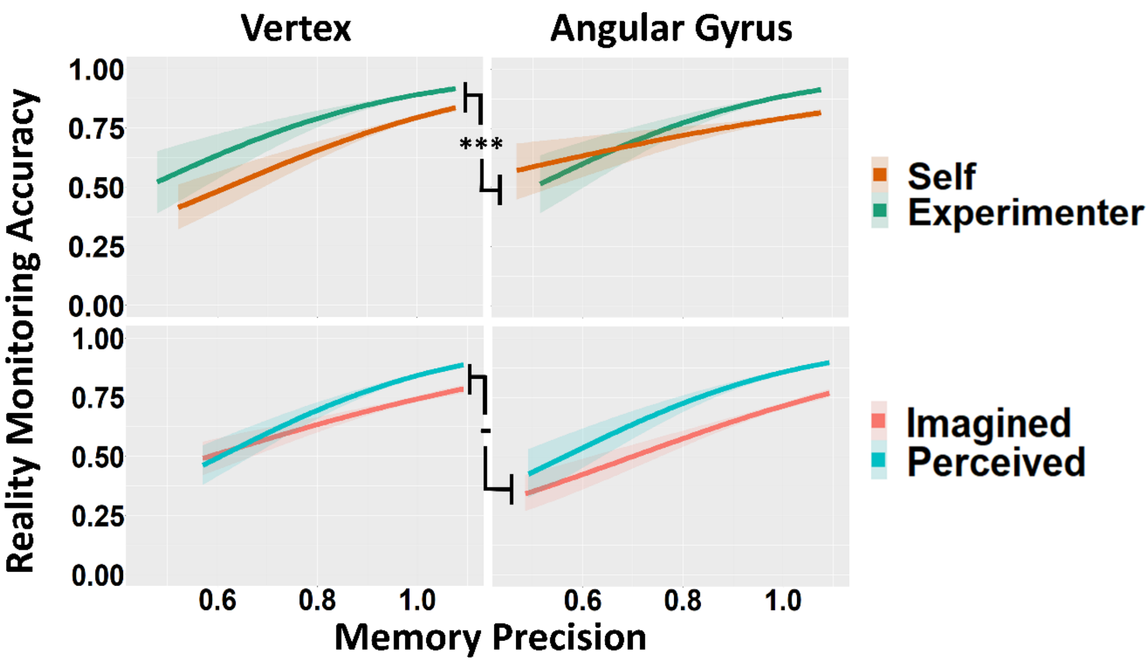

Figure 2.3. Associations Between Reality Monitoring Accuracy and Memory Precision. Plots in the top and bottom rows of the figure represent agency and perceptual reality monitoring task performance, respectively. Plots on the left and right sides of the figure represent task performance under vertex and angular gyrus stimulation, respectively. The lines represent logistic regressions, in which memory precision predicts reality monitoring accuracy. The shaded areas represent standard error of the mean. '-': $p > 0.05$, '***': $p < 0.001$.

Across-Item Level Analysis: Behavioural Experiments

The across-item-level analysis in behavioural Experiments 2.1 and 2.2 first sought to test whether average reality monitoring accuracy tend to be greater in the 'external' reality monitoring conditions, relative to 'internal' conditions, which would correspond to externalisation bias. The analysis also sought to test whether greater average reality monitoring accuracy tend to be associated with greater average memory precision, which would reflect a positive behavioural association. The analysis finally sought to test whether the behavioural association tend to stronger in the 'external' reality monitoring conditions, relative to the 'internal' conditions. The across-item-level analysis was conducted by computing fixed effects linear regression models, where the outcome variable is average reality monitoring accuracy, the predictors are average memory precision and reality monitoring conditions. These models may be formalised as the following equation: Average Reality Monitoring Accuracy$_j$ = β*Average Memory Precision$_j$ + β*Reality Monitoring Condition + Constant + Error, where 'j' represents jth participant.

These models revealed statistically significant externalisation biases, where average agency reality monitoring accuracy tend to be greater in the 'self' reality monitoring condition, relative to the 'experimenter' condition in Experiment 2.1, ($F(1,92) = 27.513$, $p < 0.001$); and average perceptual reality monitoring accuracy tend to be greater in the 'perceived' reality monitoring condition, relative to the 'imagined' condition in Experiment 2.2 ($F(1,92) = 9.144$, $p = 0.003$).

The model in Experiment 2.1 did not reveal a positive behavioural association ($F(1,92) = 3.531$, $p = 0.063$); whereas the model in Experiment 2.2 did reveal a statistically significant positive behavioural association ($F(1,92) = 27.014$, $p < 0.001$). The interaction analysis comparing the behavioural association between reality monitoring conditions did not reveal an interaction effect in both Experiment 2.1 and 2.2 ($F(1,92) = 2.651$, $p = 0.107$; $F(1,92) = 2.517$, $p = 0.116$).

Across-Item Level Analysis: Brain Stimulation Experiments

Turning to brain stimulation Experiments 2.3 and 2.4, the main analysis first sought to test whether stimulation of angular gyrus reduced both average reality monitoring accuracy and average memory precision, relative to the control site stimulation. This notion was tested by computing separate fixed effects linear regression models, where the outcome variable was either average reality monitoring accuracy or average memory precision. Across all models, the 'stimulation site' predictor was included. To also test an a-priori prediction that the possible effect of brain stimulation may be greater in the 'internal' reality monitoring conditions, relative to the 'external' conditions, the 'reality monitoring conditions' predictor was also included in all models. These models may be formalised as following equations: Average Reality Monitoring Accuracy = β*Stimulation Site + β*Reality Monitoring Condition + Constant + Error; and Average Memory Precision = β*Stimulation Site + β*Reality Monitoring Condition + Constant + Error.

Regression models concerning reality monitoring performance did not reveal an effect of brain stimulation site on average reality monitoring accuracy, relative to the control site stimulation, in both Experiments 2.3 and 2.4 ($F(1,188) = 0.058$, $p = 0.81$; $F(1,188) = 0.013$, $p = 0.91$). Models concerning memory precision also did not reveal a significant effect of brain stimulation site on average memory precision, in both Experiments 2.3 and 2.4 ($F(1,188) = 0.688$, $p = 0.408$; $F(1,188) = 0.541$, $p = 0.463$).

The interaction analysis comparing possible effects of brain stimulation site between reality monitoring conditions did not reveal an interaction effect on average reality monitoring accuracy, in both Experiments 2.3 and 2.4 ($F(1,188) = 0.178$, $p = 0.674$; $F(1,188) = 1.395$, $p = 0.239$). Interaction analysis on average memory precision also did not reveal an interaction effect, in both Experiments 2.3 and 2.4 ($F(1,188) = 0.01$, $p = 0.921$; $F(1,188) = 0.24$, $p = 0.625$).

Further analyses sought to test whether stimulation of angular gyrus reduced the behavioural association between average reality monitoring accuracy and average memory precision, relative to the control site stimulation. This analysis sought to also test whether the possible effect of brain stimulation tend to be greater in the 'internal' reality monitoring conditions, relative to the 'external' conditions. To test these notions, fixed effects linear regression models where the outcome variable is average reality monitoring accuracy additionally included the 'memory precision' predictor. This model was formalised as the following equation: Average Reality Monitoring Accuracy$_j$ = β*Average Memory Precision$_j$ + β*Stimulation Site + β*Reality Monitoring Condition + Constant + Error, where 'j' represents jth participants).

These models did not reveal an effect of brain stimulation site on the behavioural association, relative to the control site stimulation, in both Experiments 2.3 and 2.4 ($F(1,184) = 3.389$, $p = 0.673$; $F(1,184) = 0.26$, $p = 0.61$). Interaction analysis comparing the possible effect of brain stimulation site between reality monitoring conditions did not reveal an interaction effect in both Experiments 2.3 and 2.4 ($F(1,184) = 0.013$, $p = 0.91$; $F(1,184) = 0.399$, $p = 0.529$).

Discussion

Experiments in Chapter 2 aimed to investigate how we may distinguish veridical memories from products of our imagination, by testing two key questions stemming from the Source Monitoring Framework: does reality monitoring ability depend, at least partly, on the quality of the underlying mnemonic representation? and does this possible dependency involve angular gyrus? Experiment 2.1 assessed whether agency reality monitoring, the ability to distinguishing one's past actions from those performed by others, may be associated with the precision with which participants remembered the corresponding action. Experiment 2.2 assessed whether perceptual reality monitoring, the ability to distinguish imagined experiences from perceptions of the outside world, may be associated with the corresponding memory precision. Experiments 2.1 and 2.2 first revealed that participants exhibited externalisation biases, where both agency and perceptual reality monitoring performances tended to be lower in occurrences where the content of the corresponding mnemonic representation involved either participants' own actions or imagined experiences, relative to those involving either actions performed by the experimenter or perception of external events. These externalisation biases were associated with the precision of the underlying mnemonic representations, such that participants were more likely to misattribute their actions to the experimenter when the underlying memory precision was lower, and unusually precise recollections of imagined experiences were often misattributed as perceptions of past events. Experiments 2.3 and 2.4 assessed whether angular gyrus may represent a neurocognitive basis of these associations between reality monitoring performance and memory precision. Only in the 'self' reality condition, in which participants monitored their past actions as opposed to actions performed by the experimenter, stimulation of angular gyrus reduced the association between reality monitoring performance and memory precision, compared to stimulation of the control site. This finding suggests that angular gyrus may be important for imbuing our memories with a sense of self, enabling the ability to re-live past experiences, a key component of the 'autonoetic consciousness' that characterises episodic memory (Tulving, 1985).

Findings from the current behavioural data, that externalisation biases tended to be associated with qualities of the underlying mnemonic representations, are consistent with previous studies that investigated similar associations in patients with schizophrenia schizophrenia (Bentall et al., 1991; Brébion et al., 2012; Mondino et al., 2019; Seal et al., 1997; Simons et al., 2017; Waters et al., 2006; Woodward et al., 2007). Some of these previous studies concerning agency reality monitoring suggested the notion that patients tend to misattribute their past actions to others possibly because atypical qualities of patients' memory may reduce a sense of self-agency over their past actions (Bentall et al., 1991; Seal et al., 1997; Waters et al., 2006; Woodward et al., 2007). Such atypical mnemonic qualities may include lower memory precision, considering that participants in the current Experiment 2.1 tended to misattribute their actions to others, similar to the patients in previous studies, especially in occurrences where the corresponding memory precision tended to be lower. Turning to previous studies that investigated perceptual reality monitoring in patients with schizophrenia, these studies suggested that patients' imagined experiences may involve qualities that are often expected of perceptions, such as rich multisensory details, so patients may misattribute imagined experiences as perceptions of the outside world. In contrast to this view, however, participants in the current Experiment 2.2 misattributed imagined experiences as perceptions, especially in occurrences where the underlying mnemonic representations tended to be less precise. A possible explanation for this observation is that, on average, disproportionately lower precision with which participants remembered imaged, relative to perceived, experiences might have led to relatively lower reality monitoring accuracy concerning imagined experiences. Even in unusual occurrences where imagined experiences were remembered with high fidelity, however, participants were still more likely to misattribute imagined experiences as previous perceptions, rather than the other way around. It is possible that imaginings involving unusually precise qualities might have resembled qualities often expected of perceived experiences, such as rich and vivid visuoperceptual details, and, therefore, unusually precise imaginings might have been misattributed as perceived experiences (Richter, 2020).

These associations between externalisation biases and memory precision may help to resolve findings that have been mixed in studies that investigated similar associations among healthy people (Alderson-Day et al., 2019; Allen et al., 2006; Collignon et al., 2005; Garrison, Moseley, et al., 2017; Larøi et al., 2004). These previous studies have sought to test, but have not yet resolved, whether healthy people with greater proneness to hallucinations may exhibit cognitive profiles often associated with clinical psychosis, such as externalisation biases and atypical qualities of mental experiences. This mixed evidence may be due to the categorical yes-or-no responses used to measure qualities of mental experiences in these studies, which may have been limited in measuring subtle mnemonic characteristics that underlie reality monitoring decisions among healthy people. In contrast, the current behavioural experiments observed relatively robust associations between externalisation biases and precise qualities of recollection for example, possibly because using a continuous, rather than a binary, measure of mnemonic quality provided additional sensitivity that revealed the previously elusive link between qualities of mnemonic representations that underlie reality monitoring decisions among healthy people.

Turning to a possible neurocognitive basis of these dependencies between reality monitoring ability and the underlying mnemonic qualities, angular gyrus was expected to first facilitate precise recollection, which may then enhance reality monitoring performance, but current Experiments 2.3 and 2.4 did not observe evidence for such a relationship. It is, therefore, possible that angular gyrus might not always facilitate precise recollection. For example, angular gyrus may facilitate precise recollection under typical circumstances, but disruption of angular gyrus may induce other functionally connected regions to step in, resulting in apparently intact memory precision. If other functionally connected regions do indeed step in, enhancing this functional connection may increase memory precision. Accordingly, a study that stimulated a functional connection between posterior parietal regions including angular gyrus and hippocampus observed increased memory precision, substantiating the notion that interconnected regions may step in to support precise recollection (Nilakantan et al., 2017). A functional neuroimaging study, however, observed an association between greater memory precision and stronger functional connections within the posterior medial network that includes angular gyrus, but no such connections were observed within hippocampus (Cooper & Ritchey, 2019). So angular gyrus may be sufficient to support precise recollection in typical situations, without brain stimulation.

One must always be cautious, however, in attempting to interpret a null result, as it might simply reflect insufficient power or another technical deficiency such as failure to stimulate the correct underlying brain region. Because of these possible reasons, it might be that Experiments 2.3 and 2.4 were not able to observe the stimulation of angular gyrus to disrupt recollection precision. Note, however, the significant effect of stimulation of angular gyrus on the relationship between reality monitoring performance and recollection precision (discussed below), suggesting that these experiments might be capable of revealing such significant effects if they do exist.

Disrupting angular gyrus did reduce a link between the precision with which participants remembered their actions and the corresponding reality monitoring decisions in Experiment 2.3, a finding that is consistent with the notion that angular gyrus may selectively support subjective first-person perspective memories (Bonnici et al., 2018; Rugg & King, 2018; Weniger et al., 2009; Yazar et al., 2012, 2014, 2017). In typical situations where angular gyrus is intact, it may facilitate imbuing our memory with a self-agency, so that we may keep track of our past actions. Angular gyrus may ultimately enable the subjective sense of re-living our past known as ‘autonoetic consciousness’, which characterises episodic memory (Tulving, 1985).

This view is consistent with results from difference levels of analyses in Experiment 2.3, where disrupting angular gyrus reduced the item-level behavioural association between self-referential reality monitoring decisions and memory precision, both of which correspond to the respective object, relative to the control site stimulation; whereas across-item level behavioural association was intact. This selective item-level effect suggests that, in typical circumstances without brain stimulation, angular gyrus may help to imbue each remembered experience with a sense of self-agency, allowing the extent of autonoetic consciousness to vary both between experiences and rememberers.

In contrast to results in Experiment 2.3, the link between perceptual reality monitoring decisions and memory precision remained intact following disruption of angular gyrus in Experiment 2.4. These different results in Experiments 2.3 and 2.4 suggests that angular gyrus may not always process remembered experiences; angular gyrus may process self-referential memories preferentially. Note with caution, however, that this contrast between Experiment 2.3 and 2.4 is exploratory in nature and, therefore, more prone to an increased likelihood of false positive results. Moreover, the exploratory contrast between experiments is 2.3 and 2.4 less-well controlled than planned within-experiment contrasts and, therefore, between-experiment contrast should be interpreted with relatively lower level of confidence. The within-experiment contrasts reported in Experiment 2.3 were nevertheless statistically significant after accounting for the increased likelihood of false positive results, by applying multiple comparisons corrections. It is therefore plausible that, even without the between-experiments comparison, findings reported in Experiment 2.3 suggests that angular gyrus may be important for enabling autonoetic consciousness.

So it seems reasonable that, at least in Experiment 2.3, participants' autonoetic consciousness might have been disrupted and, in turn, this disruption should have reduced the corresponding agency reality monitoring performance. Participants' agency reality monitoring performance, however, remained intact. This apparently intact reality monitoring performance, despite the disrupted autonoetic consciousness, suggests that reality monitoring decisions may not solely depend on one quality of mnemonic representations. Rather, we could consider multiple qualities of mnemonic representation, so that we may keep a grasp of reality, even in situations where autonoetic consciousness is disrupted. We may, for example, adapt to consider other qualities of mnemonic representation, such as the precision with which we remember the object itself, rather than a sense that we have moved the object. Such adaptations may preserve our ability to keep track of reality, resulting in an apparently intact reality monitoring performance, even after disruption of autonoetic consciousness.

Future studies may explore this possible adaption, by first measuring multiple qualities of mnemonic representations and then investigating how they may be linked to reality monitoring abilities. Measuring multiple modalities of sensory information, such as those in visual or auditory modalities for example, may reveal a possible double dissociation: patients with schizophrenia who primarily experience auditory-verbal hallucinations may exhibit impaired auditory-verbal reality monitoring performance but intact visual reality monitoring; whereas schizophrenic patients with hallucinatory experiences mainly concerning visual modalities may exhibit the opposite pattern. Such future studies may help to reveal a currently elusive link between reality monitoring abilities and multiple qualities of underlying mnemonic representations.

In summary, the current experiments in Chapter 2 revealed that reality monitoring ability may depend, at least in part, on the quality of the underlying mnemonic representation. We tend to misattribute our past actions to others particularly in situations where memories of our actions tend to be imprecise. We may also misattribute imagined experiences as perceptions of the outside world at least partly because of two reasons: on average, imagined experiences tend to be remembered with disproportionately lower precision relative to perceived experiences, and imaginings with unusually precise qualities may resemble qualities expected of perceived experiences. Angular gyrus may be selectively involved in imbuing a sense of self agency with our memory, enabling the autonoetic consciousness that characterises episodic memory. These findings collectively support the Source Monitoring Framework’s key claim, that we consider mnemonic quality to keep track of the reality. Future studies may help to reveal how reality monitoring decisions may depend on multiple mnemonic qualities.

Chapter 3: Schemas and Reality Monitoring

Introduction

Chapter 2 in the current thesis has discussed that reality monitoring decisions may depend on the precision of underlying mnemonic qualities. Sometimes, however, we might forget precise details of past experiences and, therefore, reality monitoring decisions cannot always depend on precise recollection. To explain how we may keep track of reality in instances when the precision of recollection is reduced, the Source Monitoring Framework suggests that reality monitoring decisions might draw on mnemonic qualities more associated with semantic than episodic memory. Mnemonic qualities associated with semantic memory might include those reflected in knowledge structures that often reflect common qualities of multiple past experiences known as 'schemas' (Gilboa & Marlatte, 2017). Schemas, for example, might reflect qualities that are often associated with real past experiences, such as knowledge that visuoperceptual properties of imagined experiences tend to be distinguishable from those associated with perceived experiences. Schemas might consciously or sub-consciously exert influence over how we subsequently remember past experiences (Gilboa & Marlatte, 2017). In attempts to remember precise details of forgotten experiences, for example, we might instead retrieve schemas, which might help us to generate mental representations that are qualitatively similar to past experiences but ultimately fuzzy gist-like false memories (Brainerd et al., 2001). Some researchers have argued that this kind of false memory known as '*phantom recollection'* might induce a false sense that we might be remembering actual experiences when in fact, we are imagining those experiences (Brainerd et al., 2001). Because of such a false sense, we might mistakenly believe that imagined experiences seem familiar, even when we have not actually seen these experiences, misattributing them as perceptions of the outside world and, in turn, resulting in externalisation bias (Bayen et al., 2000; Küppers & Bayen, 2014). Experiments described in Chapter 3 aimed to test this notion, that retrieval of schemas might induce externalisation bias.

This possible link between schemas and externalisation bias may help to explain shifts in qualities of false memories across the lifespan. According to a study on false memory during childhood, for example, children tend to recall hearing words that they did not actually hear, and qualities of such false memories during early childhood may shift to become more semantic towards later years of childhood (Dewhurst & Robinson, 2004). Such a shift suggests that, as we grow up, false memories may come to reflect general semantic, rather than specific perceptual, qualities of past experiences. So, upon encountering novel lures that are semantically similar to qualities of past experiences, we may experience a false sense of familiarity, especially as we get older (Dewhurst & Robinson, 2004; Mitchell et al., 2003). Consistent with this view, older adults tend to be more confident that they have seen information that was only suggested to them, relative to younger adults (Mitchell et al., 2003). Such studies, that collectively investigated false memory across the lifespan, suggest a possible association between schemas and a false sense of familiarity. Such false senses of familiarity may induce misattribution of imagined experiences to external sources, resulting in externalisation biases, especially as our schema develops across the lifespan.

In contrast to this view, however, studies on reality monitoring between different age-groups have not always observed a possible increase in magnitudes of externalisation bias between, for example, younger and older children (Markham, 1991; Markham et al., 1999; Sluzenski et al., 2004; Sussman, 2001), children and young adults (Lindsay & Johnson, 1991), and younger and older adults (Cohen & Faulkner, 1989; Mammarella & Cornoldi, 2002; McDaniel et al., 2008). This mixed evidence suggest that a possible link between schemas and an externalisation bias remains elusive.

A possible reason for this mixed evidence is that schemas derived from everyday experiences might be irrelevant to the kinds of experiences tested in laboratory experiments. To test whether schemas might influence reality monitoring decisions, experiments must involve participants first developing new schemas that more closely relate to the experiences tested in the experiment. Such experiments may help to reveal whether schemas might be associated with reality monitoring decisions. Experiment 3.1 sought to test this idea by adapting an experimental paradigm from a previous study on schema (Richter et al., 2019). Richter et al.'s participants were asked to view objects from four categories (animals, clothes, furniture and food) presented around a circular space. For each category, most of the objects were presented within 90º segments of the circle, or quadrants, so that participants might come to sub-consciously associate quadrants with object categories, gradually developing a schema about visuospatial qualities of these objects. Experiment 3.1 modified this experimental paradigm, such that objects were divided into two schema presence conditions: in the 'schema present' condition, participants were asked to either imagine or perceive objects progressively moving to distinct quadrants; whereas in the 'schema absent' condition, participants either imagined or perceived objects progressively moving to random locations around a circle. This procedure was designed to help participants to develop a schema that reflects qualities of imagined and perceived experiences in the ‘schema present’ condition, relative to the ‘schema absent’ condition.

Even if such schemas are associated with externalisation bias, however, precise recollection of each experience may facilitate reality monitoring decisions (see Chapter 2), obscuring a possible link between schemas and externalisation bias. To test this possible link, therefore, recollection performance might need to be reduced. Recollection performance may be reduced by including a longer delay between study and test phases of a memory task, as in previous studies that compared the precision with which we retrieve working and long-term memory (Biderman et al., 2019; Korkki et al., 2020). These studies have observed that the precision of memory tend to degrade over time, suggesting that a longer delay period between study and test phases might reduce recollection performance. So it seems plausible that including a long delay period in Experiment 3.1 might reduce participants’ recollection performance, compared to an immediate memory test. If recollection performance is indeed reduced, for example, participants might randomly guess the location of objects and, in turn, randomly indicate that the object was encoded in either ‘imagined’ or ‘perceived’ reality condition.

In contrast, even after a long delay, the influence schemas have on participants’ memory ability, or ‘schematic memory performance’, might be preserved. Participants might, for example, randomly place an object in a quadrant but indicate that the object was encoded in the reality condition associated with that quadrant, reflecting a possible influence of schemas on reality monitoring decisions. In line with this view, a previous study on schemas observed that a 24-hour delay often facilitates consolidation of schemas, relative to no delay, suggesting that a 24-hour delay might enhance a possible influence of schema on subsequent mnemonic processes (Richter et al., 2019). Based on such findings, Experiment 3.1 divided participants into either ‘24-hour-delay’ or ‘immediate’ memory test groups, so that recollection performance might be reduced in the ‘24-hour-delay’ memory test group, relative to schematic memory performance. Such results would suggest a distinction between recollection of specific details and the possible influences that schemas might have on reality monitoring decisions, reducing the likelihood of precise recollection confounding a possible link between schemas and externalisation bias.

The schemas may influence reality monitoring decisions via two kinds of mnemonic advantages. The first kind, known as the ‘congruency advantage’, refers to a phenomenon where qualities of experiences that are congruent with a schema are often remembered better than unrelated qualities (Greve et al., 2019; Sterzer et al., 2018; Van Kesteren et al., 2012). When qualities of new experiences are congruent with a schema, for example, recollection of these experiences tends to be more precise (Richter et al., 2019). Precise mnemonic representations may clearly resemble qualities that are often expected of imagined and perceived experiences, enabling more accurate reality monitoring decisions based on recollection (see findings in both Experiments 2.2 and 2.4 in Chapter 2). In contrast, the 'incongruency advantage' involves a signal that often reflects a discrepancy between qualities of new experiences and a schema known as the '*prediction error*' (Greve et al., 2019; Sterzer et al., 2018; Van Kesteren et al., 2012). Prediction errors might induce a sense that qualities of new experiences are unfamiliar and, because of such senses, we might accurately indicate that we have not actually seen experiences that were in fact, products of our imagination.

While both congruency and incongruency advantages may enhance reality monitoring performance, rates at which these advantages increase reality monitoring performance might reveal a possible link between schemas and externalisation bias. Encountering new experiences that share congruent qualities, for example, may strengthen schemas, increasing reality monitoring performance over these experiences. In contrast, incongruent qualities may be associated with prediction errors, which may first shift the initial schema, so that the later schema may come to assimilate previously incongruent qualities of new experiences. During this shift from the initial to the later schema, the strength of these schema may be weaker than those that have been constantly strengthened by congruency advantage, resulting in a slower increase in reality monitoring performance. Taken together, both congruency and incongruency advantages may enhance reality monitoring performance, but congruent qualities of experiences may strengthen schemas faster, relative to incongruent qualities, resulting in a greater rate of increase in reality monitoring performance or '*learning rate*'.

Predictions regarding learning rates concern both congruency and incongruency advantages. Congruency advantage may, for example, equally strengthen schemas that reflect qualities of imagined and perceived experiences, so learning rates associated with imagined and perceived experiences may be comparable, maintaining the magnitude of a possible externalisation bias. In contrast, incongruency advantage may particularly concern relative strengths of schemas that reflect qualities of imagined and perceived experiences. If, for example, a schema that reflects qualities of perceived experiences tends to be stronger than one that reflects qualities of imagined experiences, incongruency advantage may induce stronger prediction errors associated with perceived experiences, resulting in a disproportionately greater learning rate for perceived experiences, relative to imagined experiences. Such disproportional learning rates may gradually lead to greater reality monitoring performance for perceived experiences, relative to imagined experiences, ultimately resulting in greater externalisation bias. Experiment 3.2 sought to test these predictions, that congruency advantage may result in comparable learning rates associated with imagined and perceived experience; whereas incongruency advantage may result in a disproportionately faster learning rate for perceived experiences, relative to imagined experiences and, therefore, greater externalisation bias, relative to congruency advantage.

Overall, experiments in Chapter 3 sought to investigate a question that stems from the Fuzzy Trace Theory: does a schema induce an externalisation bias? Experiment 3.1 aimed to develop an experimental paradigm that might help participants to develop schemas, and to reduce recollection performance while preserving schematic memory performance. Experiment 3.2 aimed to test whether learning rates associated with congruent qualities of experiences tend to be faster, relative to incongruent experiences; and whether learning rates tend to be faster over perceived experiences, relative to ones that were imagined, resulting in an externalisation bias. The magnitude of externalisation bias associated with incongruent qualities of experiences was predicted to be greater, relative to congruent qualities.

Methods

Participants

A total of 80 participants between 18 to 35 years of age were included in the analysis. Experiment 3.1 included 32 participants, and Experiment 3.2 included 48 participants. All participants were included in only one of the Experiments 3.1 or 3.2. All participants reported normal vision and hearing, no history of neurological or psychiatric conditions, and provided informed consent in accordance with the procedure approved by the University of Cambridge Human Biology Research Ethics Committee.

Stimuli

Stimuli in the current experiments were modified from Chapter 2. Each display consisted of an image of a real-world object overlaid on a faint patterned background. A total 320 displays were used (see Figure 3.1 for an illustration of the stimuli).

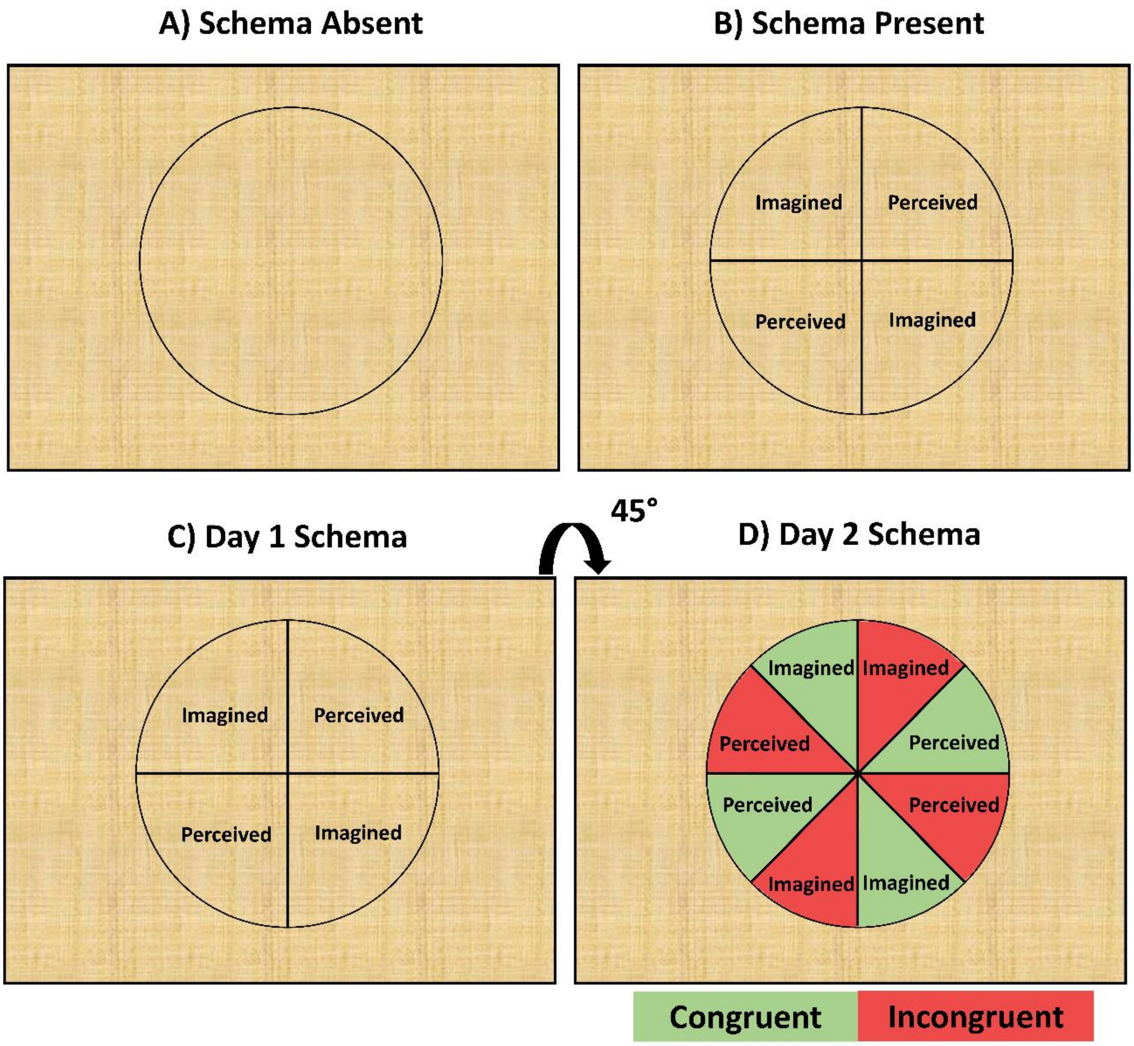

Figure 3.1. Illustration of the Stimuli. In Experiments 3.1, half of the objects progressively moved from the centre of the computer screen to random locations around the circle (A), whereas the other half moved to distinct quadrants, such that objects that moved to top-right and bottom-left quadrants were perceived, and ones that moved to top-left and bottom-right were imagined (B). In Experiment 3.2, object locations in day 1 consisted of distinct quadrants, as in the schema present condition of Experiment 3.1 (C). These object locations from day 1 were rotated 45º clockwise in day 2 (D), so locations of objects associated with perceived and imagined experiences in day 2 were either congruent or incongruent with locations of objects in day 1.

In Experiment 3.1, displays were divided into two schema presence conditions. In the ‘schema absent’ condition, target locations of objects were randomly assigned. In the ‘schema present’ condition, each quadrant was first given possible target locations: a thousand locations normally distributed around the centre of each quadrant (i.e., 45º, 135º, 225º, and 315 º). To match the number of target locations on either sides of the quadrat and, therefore, reduce the likelihood of clustering target location, twenty of these possible locations from each half of the quadrant were randomly sampled, so that the locations were not concentrated only on one half of the quadrant. These sampled locations were assigned as target locations of the objects in the ‘schema present’ condition. Among these objects, ones with target locations at the top-right and bottom-left quadrants were allocated to the ‘perceived’ reality condition, whereas objects in top-left and bottom-right quadrants were allocated to the ‘imagined’ reality condition.

In Experiment 3.2, displays were randomly allocated to either day 1 or 2 of the experiment. On day 1, target locations of objects were schematised, as in the ‘schema present’ condition of Experiment 3.1. So, in each quadrat, reality conditions of objects were either imagined or perceived. Target locations of objects from day 1 were rotated 45º clockwise and, in turn, assigned as target locations of objects on day 2. So reality conditions of objects in days 1 and 2 were either congruent or incongruent, thereby enabling Experiment 3.2 to test whether schemas developed in day 1 may induce congruency and incongruency advantages in day 2, ultimately influencing reality monitoring performance.

Procedures

In both Experiments 3.1 and 3.2, participants were tested in person. In Experiment 3.1, I tested 12 participants, and a summer research student (i.e., Eddie Xiao) tested 20 participants. All participants in Experiment 3.2 were tested by me. Stimuli in both Experiments were presented on a computer screen, using Psychtoolbox (version 3.0.14) and Matlab (version 2018b).

Experiment 3.1: Developing a Schema and Reducing Recollection

Participants were split into two memory test delay groups: the ‘immediate memory test’ group, in which each study phase was followed by an immediate memory test phase; and the ‘delayed memory test’ group, in which each study phase was first followed by a 24-hour delay and then the respective memory test phase. Participants in the ‘immediate memory test’ group were asked to complete 2 sets of study-test cycles. Each set consisted of 10 study-test cycles, and 16 displays were presented in each cycle. Participants in the delayed memory test group was also asked to complete 2 sets of study-test cycles, but each set consisted of only one study-test cycle, and 160 displays were presented in each cycle.

In both the immediate and delayed memory test groups, each set consisted of displays in either the ‘schema absent’ or ‘schema present’ conditions, and the order of schema presence conditions were counterbalanced between sets. Half of the displays in each study-test cycle were in the ‘imagined’ reality condition, and the other half were in the ‘perceived’ reality condition. Participants completed a practice task before starting the first study phase.

Procedures of each study and test phase trials in Experiment 3.1 was identical to ones in Experiment 2.2 of Chapter 2. In each study phase trial, an object was presented at the centre of the computer screen (3s). Then in the ‘imagined’ condition, the object was replaced by a black cross, and participants were asked to imagine the object moving progressively to the target location as the cross moved progressively to the target location (1s). In the ‘perceived’ condition, participants were asked to watch the object move progressively to its target location (1s). When the cross or the object reached its target location, participants were asked to think about what the object was, where its target location was, and whether the movement of the object was imagined or perceived (3s).

In each test phase trial, studied objects were presented at random locations around a circular space. Participants were asked to first recreate the target location of each object by pressing the left and right arrow keys, which moved the object anti-clockwise and clockwise around the circular space, respectively. Participants were also asked to decide whether the movement of the object was imagined or perceived by pressing the ‘I’ and ‘P’ keys, respectively. The trials were subject paced, terminating if participants did not respond after 9s. A text reminder of what each key represented was presented in the middle of the computer screen, which turned red to indicate when 3s was left before the trial expired.

Experiment 3.2: Manipulating a Schema

Procedures of Experiment 3.2 were identical to the ‘schema present’ condition of the ‘delayed memory test’ group in Experiment 3.1, except for following procedures: on day 1, participants were asked to study 160 displays. On day 2, participants were asked to complete 4 study-test cycles. In each cycle, participants were first asked to study 40 displays, and during the following test phase, participants were tested on 40 displays from day 1 and 2 each, thereby testing participants’ memory of all displays from both days. See Figure 3.2 for an overview of procedures in Experiments 3.1 and 3.2.

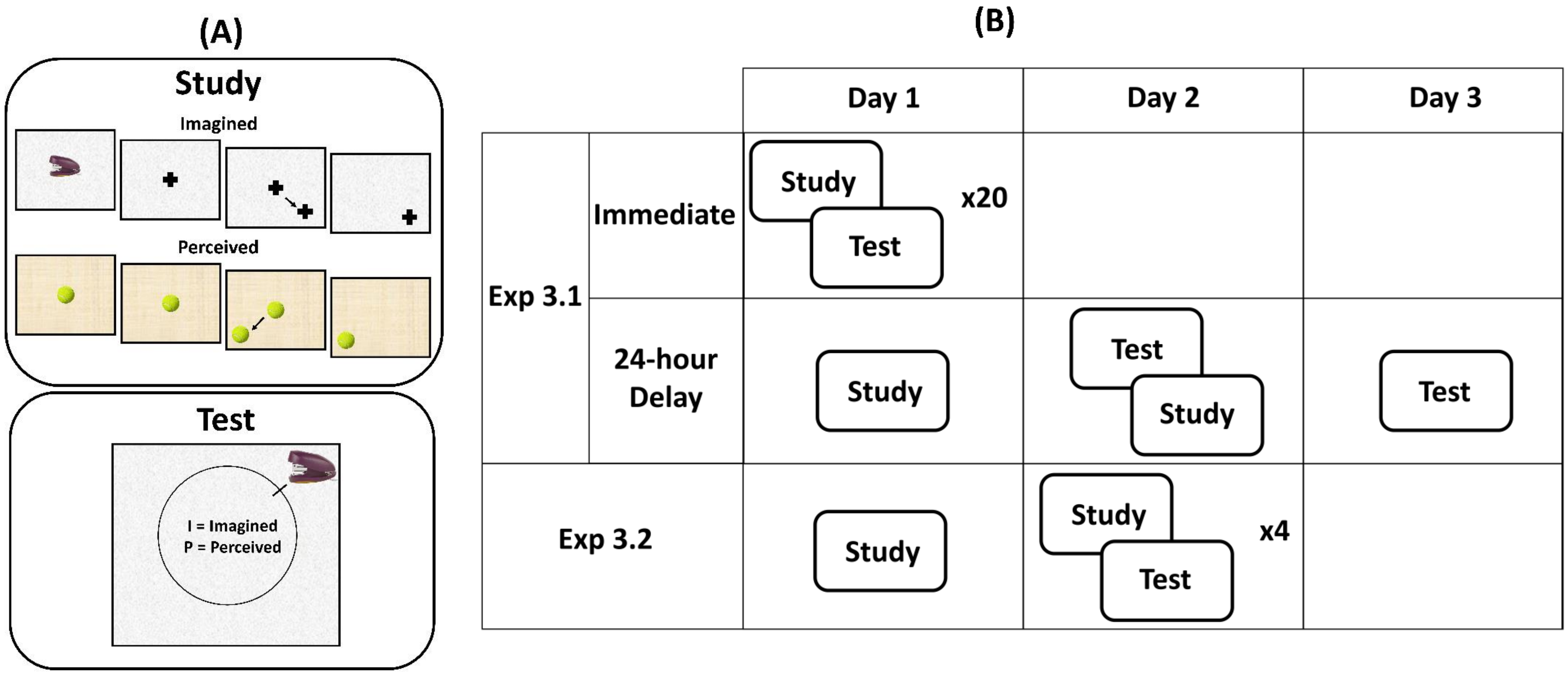

Figure 3.2. Procedures in Experiments 3.1 and 3.2. Study and test phase trials were identical in both experiments (A). Participants were first asked to either imagine or perceive objects progressively moving to their target location. In the following test phase trials, participants were asked to recreate the target location and indicate whether the movement of the object was either imagined or perceived, by pressing ‘I’ or ‘P’ keys, respectively. The delay periods between study and test phases were different in Experiments 3.1 and 3.2 (B): half of the participants were asked to progress from a study phase to the following test phase immediately, and the other half were asked to return 24-hours after each study phase. In Experiment 3.2, the first study phase was followed by a 24-hour delay, and subsequent study phases were followed by immediate test phases.

Analysis Approach

Experiment 3.1 first sought to measure the accuracy with which participants distinguished common qualities of imagined experiences from those of perceived experiences. Participants might have, for example, placed an object at any location around a circle and, in turn, indicated that the object was encoded in a reality condition associated with the respective quadrant, reflecting an accurate 'schematic memory' response. The number of accurate schematic memory responses was divided by the total number of trials, providing a measure of schematic memory accuracy.

To test whether a longer 24-hour delay between study and test phases reduced recollection, relative to no delay, Experiment 3.1 sought to also measure the accuracy with which participants recollected locations of each object. If participants remembered the target location, for example, participants might have placed the object at a location that was at least within either 90º degrees to the left and right of the target location, reflecting an accurate recollection memory response. The number of accurate recollection responses was divided by the total number of trials, providing a measure of whether or not participants remembered the location of each object. This measures of recollection accuracy was used in the Current Chapter 3 (rather the measure of precision with which participants successfully retrieved the location in Chapter 2). If recollection accuracy tend to be at chance-level performance (i.e., 50%), for example, it may reflect unsuccessful recollection (rather than precision with which participants successfully retrieved the target location).If retrieval was indeed unsuccessful following the 24-hour delay, relative to no delay, memory precision might have been unlikely to influence reality monitoring accuracy. In contrast, a bias to misattribute imagined experiences as previous perception of the outside world, more than the other way around, may influence reality monitoring accuracy to be lower in the imagined reality monitoring condition relative to the perceived condition.

Experiment 3.2 sought to test whether a schema developed in day 1 might induce both congruency and incongruency advantages, facilitating reality monitoring decisions that concern displays studied in day 2. To test this notion, reality monitoring accuracy was measured for each study-test cycle in day 2 or 'blocks' 1 to 4.

Assumptions of statistical models in both Experiments 3.1 and 3.2 were assessed, using similar analysis approaches reported in Chapter 2. These approaches include, for example, visual inspection of linearity between log of the outcome variable and the predictor, and removal of potential outliers.

Statistical power analysis in Experiment 3.1 was conducted for a regression model, where the outcome variable (schematic memory accuracy) was predicted by two repeated-measures factors (schema presence condition and reality monitoring condition) and a between-participants factor (memory test groups). It revealed that 24 participants were needed to detect a medium size effect ($f = 0.25$, $\alpha = 0.05$, $1\text{-}\beta = 0.8$). To ensure counter-balancing for the memory test group factor, however, 32 participants were included in the main analyses ($f = 0.25$, $\alpha = 0.05$, $1\text{-}\beta = 0.91$). This power analysis was conducted in Gpower version 3.1.0.

Statistical power analysis in Experiment 3.2 was conducted for a regression model, where the outcome variable (reality monitoring accuracy) was predicted by three repeated-measures factors (reality monitoring condition, study-test block number, and schema congruency). It revealed that 37 participants were needed to detect a medium size effect ($f = 0.25$, $\alpha = 0.05$, $1\text{-}\beta = 0.8$). To counter-balance the order between Experiment 3.2 and a separate counterpart experiment (which is not reported in the current thesis), however, 48 participants were recruited in Experiment 3.2 ($f = 0.25$, $\alpha = 0.05$, $1\text{-}\beta = 0.952$). This power analysis was conducted in R, using the 'pwr.f2.test' function in the 'pwr' package.

The main analyses in the current chapter were conducted in 'R', using multiple statistical functions and packages: both repeated measures and mixed ANOVAs were conducted using the 'ezANOVA' function in the 'ez' package; logistic regressions were conducted using the 'glmer' function in the 'lme4' package; repeated measures t-tests were conducted using the 't.test' function, which is a base function built into R.

Results

Greater Schematic Memory Performance is Associated With The Schema Presence Condition

Analyses in Experiment 3.1 first aimed to test a possible main effect of schema presence on schematic memory performance. Schematic memory accuracy was expected to be greater in the 'schema present' condition relative to the 'schema absent' condition. This main effect was expected across all reality conditions and memory test delay groups. To test for this possible main effect, a mixed effects Multivariate Analysis of Variance (MANOVA) was conducted on schematic memory accuracy, with repeated-measures factors of both the schema presence condition and the reality monitoring condition, and a between-participants factor of memory test groups. This MANOVA revealed that schematic memory accuracy tended to be significantly greater in the ‘schema present’ condition (*M* = 82.902%, *SE* = 2.989%) relative to the ‘schema absent’ condition (*M* = 52.212%, *SE* = 1.016%) ($F(1,30) = 109.269$, *ges* = 0.556, $p < 0.001$). The MANOVA did not, however, reveal a main effect of reality condition ($F(1,30) = 1.666$, *ges* = 0.001, $p = 0.207$) or memory test group ($F(1,30) = 3.915$, *ges* = 0.05, $p = 0.057$). No statistically significant interactions were observed between the factors of schema presence, reality conditions, and memory test groups ($F(1,30) <= 1.602$, *ges* <= 0.001, $p > 0.05$).

Reduced Recollection Performance is Associated with A Longer Memory Test Delay

Analyses in Experiment 3.1 then aimed to test whether recollection memory accuracy tended to be lower in the delayed relative to immediate memory test group. This possible main effect of memory test delay group was expected across both reality monitoring and schema presence conditions. A MANOVA testing for this possible main effect revealed that recollection memory accuracy tended to be significantly lower in the ‘delayed memory test’ group (*M* = 53.552%, *SE* = 1.819%), relative to the ‘immediate memory test’ group (*M* = 77.879%, *SE* = 2.727%) ($F(1,30) = 67.079$, *ges* = 0.584, $p < 0.001$). This MANOVA also revealed a significant interaction between memory test delay groups and reality conditions ($F(1,30) = 5.125$, *ges* = 0.03, $p = 0.003$).

Follow-up pair-wise t-tests testing for possible effects of reality condition on recollection memory accuracy were conducted in each memory test group. Tests concerning the delayed memory test group observed no significant difference in recollection memory accuracy between imagined and perceived reality conditions (*M* = 53.067%, *SE* = 2.171%; *M* = 53.037%, *SE* = 2.087%) ($t(1,31) = 0.64$, $d = 0.226$, $p = 0.527$); whereas in the immediate memory test group, recollection memory accuracy tended to be significantly lower in the ‘imagined’ reality condition (*M* = 73.789%, *SE* = 3.193%), relative to the ‘perceived’ reality condition (*M* = 81.968%, *SE* = 3.16%) ($t(1,31) = 3.664$, $d = 2.767$, $p < 0.001$).

Externalisation Bias is Associated with a Disproportionately Greater Learning Rate Concerning Perceived Experiences, Relative to Imagined Experiences.

Analyses in Experiment 3.2 first aimed to test whether reality monitoring accuracy concerning imagined experiences was lower, relative to those concerning perceived experiences, resulting in an externalisation bias. The magnitude of externalisation biases was predicted to be greater if the quadrants associated with reality conditions in day 1 was incongruent with reality conditions in day 2, relative to whether they were congruent. A repeated measures ANOVA was conducted on reality monitoring accuracy, testing for both this possible main effect of reality condition, and a possible interaction between reality condition and schema congruency. This ANOVA revealed that reality monitoring accuracy concerning imagined experiences tended to be significantly lower (M = 54.91%, SE = 2.19%), relative to perceived experiences (M = 68.77%, SE = 1.602%) ($F(1,47) = 28.949$, $ges = 0.292$, $p < 0.001$), revealing an externalisation bias across ‘schema congruency’ conditions. No significant interaction was observed, however, between reality conditions and schema congruency conditions ($F(1,47) = 1.441$, $ges = 0.004$, $p = 0.236$).

Subsequent analyses aimed to test whether reality monitoring accuracy might increase from study-test blocks 1 to 4. A logistic regression testing for this possible increase was conducted, in which the predictor variable was the study-test block numbers, the outcome variable was reality monitoring accuracy, and the random effects variable was participant. This model was formalised as the following equation: ‘$Reality\ Monitoring\ Accuracy_{ijk} = \beta * Study\_Test\_Block_i + Constant + Error$’, where the ‘$\beta$’ represents the regression coefficient and the ‘i’ represents the ith participant, ‘j’ represents the jth reality monitoring condition, and ‘k’ represents kth congruency condition. This regression revealed a significantly positive association between study-test blocks and reality monitoring accuracy ($\beta = 0.13$, $R^2 = 0.038$, $p < 0.001$). The coefficient of this positive association may reflect a rate at which participants learn the later schema, so this rate is referred to the ‘learning rate’ in subsequent analyses.

The learning rate was predicted to be faster in the congruent relative to incongruent ‘schema congruency’ condition, a possible main effect of schema congruency. Learning rate was also predicted to be faster in the perceived relative to imagined reality condition, especially in the incongruent relative to the congruent condition, a possible interaction between schema congruency and reality conditions. A repeated measures ANOVA testing for both these possible main effects and interaction revealed that reality monitoring accuracy tended to increase significantly faster in the ‘schema congruent’ condition (M = 0.245, SE = 0.003), relative to the ‘schema incongruent’ condition (M = 0.113, SE = 0.003) ($F(1,47) = 35.636$, $ges = 0.1$, $p < 0.001$). This ANOVA also revealed a significant interaction between schema congruency and reality conditions ($F(1,47) = 7.027$, $ges = 0.02$, $p = 0.011$). The follow-up pair-wise t-tests revealed that the learning rate tended to be greater in the ‘perceived’ reality condition (M = 0.171, SE = 0.003), relative to the ‘imagined’ reality condition (M = 0.055, SE = 0.004) but only in ‘schema incongruent’ condition ($t(1,47)$ =

3.72, $d = 0.759$, $p < 0.001$). No such significant effect of reality condition was observed in the 'schema congruent' condition ($t(1,47) = 0.152$, $d = 0.031$, $p = 0.88$). See Figure 3.3 for an overview of the main results).

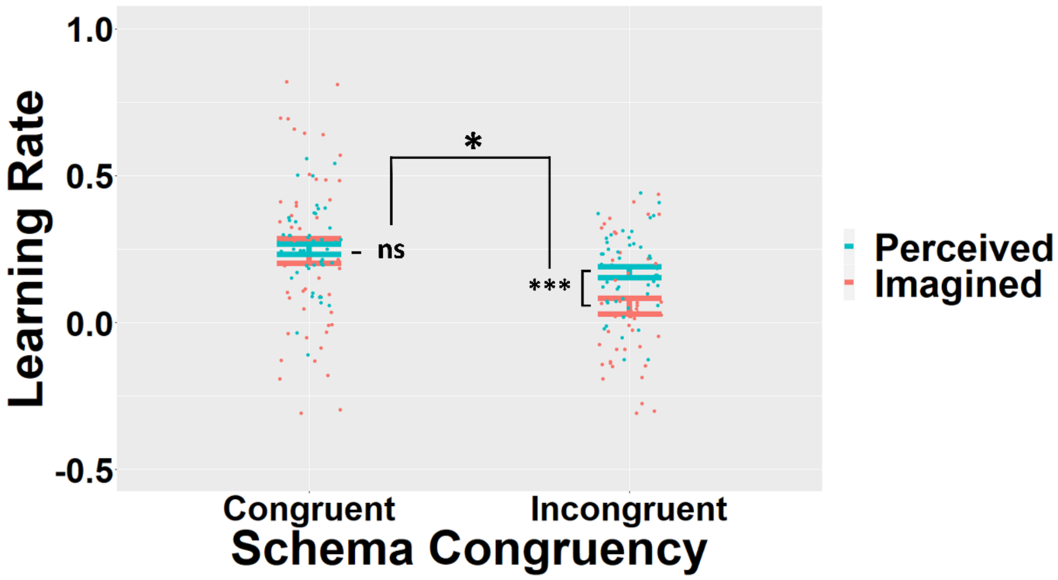

Figure 3.3. Mean Learning Rates. Only when the qualities of experiences reflected in a schema was incongruent, learning rates concerning perceived experiences tended to be greater, relative to those concerning imagined experiences. Error bars represent respective standard errors of the mean. 'ns': $p > 0.05$, '***': $p < 0.001$.

Discussion

Experiments in the current chapter aimed to test the notion that a schema may induce an externalisation bias. In order to test this notion, Experiment 3.1 first sought to help participants develop schemas that reflect qualities of either imagined or perceived experiences, by asking them to either imagine or perceive objects moving to quadrants of visuoperceptual locations around a circle. Consistent with this aim, participants were able to indicate which quadrants had been associated with either imagined or perceived experiences, suggesting that participants may have indeed developed schemas that reflect distinct visuoperceptual qualities of imagined and perceived experiences or a 'reality schema'. Even though such a schema may have been associated with an externalisation bias, this possible association could have been confounded by a link between precise recollection and reality monitoring (see findings in Chapter 2). To reduce the likelihood of this possible confound, Experiment 3.1 additionally sought to reduce recollection performance, while preserving a possible effect of schemas on reality monitoring decisions, by including a 24-hour delay between study and test phases. Consistent with this aim, recollection memory performance was often lower in a group of participants that were given the 24-hour delay, relative to a group that was not given a delay. In contrast, participants in both groups were still able to indicate distinct quadrants that had been associated with imagined and perceived experiences, suggesting a dissociation between recollection and schemas in the current experimental paradigm. Experiment 3.2 went on to test a possible association between schemas and an externalisation bias. It was predicted that strengthening a schema might increase reality monitoring performance. Only when quadrants associated with imagined and perceived experiences in day 1 were incongruent with those in day 2, the rate of increase in reality monitoring performance or 'learning rate' concerning imagined experiences tended to be disproportionately slower, relative to those concerning perceived experiences, resulting in an externalisation bias. This finding suggests that a schema that reflects qualities of imagined experiences may be weaker, relative to those reflecting perceived experiences. In turn, a weaker prediction error concerning imagined experiences may have induced a slower learning rate associated with imagined experiences, ultimately resulting in an externalisation bias. These findings collectively suggest the notion that a schema that reflects qualities of imagined and perceived experiences or a '*reality schema*' tends to be associated with externalisation biases.

The dissociation observed between recollection and a possible effect of a reality schema on reality monitoring decisions is consistent with a notion from the Fuzzy Trace Theory, that a memory system that supports recollection of precise or 'verbatim' mnemonic traces may be distinguishable from one that supports imprecise or 'fuzzy mnemonic traces', such as a reality schema (Brainerd et al., 2001). According to this notion, a reality schema could induce a sense that a mental representation feels familiar, even without recollection. This notion is also in line with the 'guessing hypothesis', which suggests that we may sometimes guess the original sources of memory based on a sense of familiarity, rather than precise recollection of details in each experience, resulting in misattribution errors (Bayen et al., 2000; Küppers & Bayen, 2014). So a reality schema may indeed be associated with reality monitoring performance.

Slower learning rates concerning incongruent qualities of experiences, relative to those concerning congruent qualities, observed in Experiment 3.2 suggests that there may be at least two kinds of possible associations. The first kind of association may involve the congruency advantage, which may help us remember congruent qualities of experiences better than unrelated qualities, enhancing reality monitoring performance based on recollection; whereas the second kind of association may involve the incongruency advantage, in which prediction errors may induce a sense that qualities of experiences are unfamiliar, facilitating reality monitoring decisions based on the sense of familiarity (Greve et al., 2019; Sterzer et al., 2018; Van Kesteren et al., 2012). So both congruency and incongruency advantages may separately facilitate links between a reality schema and reality monitoring performance.

One of the more distinguishable links may be between a reality schema and an externalisation bias that was observed only in circumstances where qualities of experiences tend to be incongruent with each other. This specific association suggests that a reality schema may induce an externalisation bias via the incongruency advantage, rather than congruency advantage. If the strength of a schema concerning the qualities of imagined experiences tended to be weaker, relative to one concerning qualities of perceived experiences for example, this weaker schema may have evoked a weaker prediction error. Such weak prediction errors may have induced a weak or false sense of familiarity, resulting in a slower learning rate concerning imagined experiences and, in turn, an externalisation bias. So it seems reasonable that we may misattribute imagined experience as perceptions of the outside world based on false senses of familiarity, even without recollection, especially in situations where qualities of mental representations underlying reality monitoring decisions are incongruent with qualities of past experiences often reflected in a reality schema.

This link between incongruency advantage and externalisation bias suggests a possibility that, as we go through more experiences across the lifespan, the magnitude of externalisation bias may increase. Newly born infants, for example, might have come across a small number of experiences and, therefore, their reality schema might not be fully developed yet. So an infant’s reality schema may be less likely to influence reality monitoring decisions, although evidence for this notion remains limited. In contrast, older adults might have had a wealth of experiences, helping them to develop a strong reality schema throughout their life and, in turn, such a strong reality schema may induce externalisation bias. Consistent with this view, a previous study compared a possible effect of pre-existing knowledge on reality monitoring decisions between older and younger adults, revealing that older adults were more likely to misattribute predicted, but not actually presented, parts of experiences as perceptions of the outside world, relative to younger adults (Mammarella & Cornoldi, 2002). A possible reason for this link between externalisation bias and healthy aging is that the precision with which older adults remember past events tend to be reduced relative to younger adults (Korkki et al., 2020; Nilakantan et al., 2018), so older adults' reality monitoring decisions may depend on qualities often associated with semantic information, such as those reflected a reality schema, rather than precise perceptual qualities associated with recollection (Mitchell et al., 2003).

In summary, experiments in the current chapter revealed that a reality schema may indeed induce externalisation bias. A disproportionately weaker schema concerning imagined experiences, relative to perceived experiences, may be associated with a weaker prediction error. Such weak prediction errors may then induce weak or false sense of familiarity, so the rate at which we learn qualities of imagined experiences may be disproportionately slower, relative to those concerning perceived experiences and, therefore, we may manifest an externalisation bias. These findings are consistent with a notion that stems from both the 'Fuzzy Trace Theory' and the 'guessing hypothesis', that we may misattribute imagined experiences as perceptions based on false sense of familiarity, rather than recollection.

Chapter 4: Individual Differences in Recollection Precision and Psychosis Traits

General Introduction

There are substantial individual differences in the precision with which people remember events. If a person's recollection precision is generally lower than average, for example, the person may be prone to misattributing internal or external sources of mnemonic representations (see Chapter 2). Such misattributions have been reliably observed in patients with schizophrenia, who often manifest traits of psychosis such as hallucinations (Simons et al., 2017). A previous study sought to test the view that psychotic traits might be associated with reduced memory quality, by investigating whether the precision of memory tends to be worse among patients with schizophrenia, relative to healthy people (Gold et al., 2010; c.f. Bays, 2010). Patients' precision of recollection, however, was often comparable to those of healthy people, providing limited support for the notion that quality of mnemonic representations may be linked to psychosis traits. In contrast, evidence for this link has been observed in a study involving a relatively larger sample of healthy people (Xie et al., 2018). People who exhibited lower precision of recollection tended to exhibit a greater extent of psychosis traits, suggesting that adopting an individual differences approach involving a large sample of healthy people may have helped to unveil a previously elusive link between mnemonic qualities and psychosis traits. This view is consistent with a theoretical account of psychosis known as the '*psychosis continuum model*', which postulates that the extent of psychosis traits may vary on a continuum from clinical to healthy people. According to this view, healthy people may indeed exhibit psychosis traits and their associated cognitive profile, such as reduced qualities of mental experiences (Meehl, 1962). Experiments in Chapter 4 sought to test this notion, that the quality of mnemonic representations may be associated with psychosis traits among healthy people.

Experiment 4.1: Introduction

A possible link between the quality of recollection and psychosis traits may involve two intermediate stages of processes. The first stage concerns findings from Chapter 2, that lower memory precision is associated with lower reality monitoring performance. This finding suggest that people whose quality of memory tend to be reduced may exhibit lower reality monitoring performance. These people may then, in the second stage, struggle to distinguish between imagined experiences and actual events in everyday-life, disrupting their relation with reality. If such difficulties persist, people may develop traits of psychosis. Previous studies involving large samples of healthy people have sought to test this notion, that reality monitoring performance may be lower among people who exhibit a greater extent of psychosis traits, but these studies have produced mixed evidence (Alderson-Day et al., 2019; Allen et al., 2006, 2006; Collignon et al., 2005; Garrison, Moseley, et al., 2017; Larøi et al., 2004).

This mixed evidence may be due to different ways in which mnemonic qualities, such as the precision or vividness of recollection, might be related to reality monitoring performance. Precise recollection, for example, may enhance reality monitoring performance (see Chapter 2); whereas subjectively vivid, but objectively false, recollection may induce a false sense of familiarity, reducing reality monitoring performance (Mondino et al., 2019; Chapter 3). According to this view, greater precision of recollection may help us to keep track of reality and, therefore, be associated with lower psychosis traits, whereas greater vividness of recollection may be associated with greater psychosis traits. These different relationships between mnemonic qualities and psychosis traits may have been challenging to distinguish in previous studies, because those studies used average reality monitoring performance to infer the underlying mnemonic qualities, conflating different ways in which each mnemonic quality may be related to reality monitoring performance and, in turn, psychosis traits. To test these possible relationships, Experiment 4.1 sought to measure both the precision and vividness of recollection.

To measure the precision of mnemonic representations that may be linked to psychosis traits, Experiment 4.1 adapted a precision memory paradigm that has previously been used to test for a link between precision of memory and psychosis traits (Xie et al., 2018). Xie et al.'s participants were asked to memorise distinct colours of objects, and during the later memory test, participants were asked to recreate the colours of each object on a continuous colour wheel, measuring the precision with which participants remembered the colour feature of objects. That study observed that people with less precise memory of the colours of objects tended to exhibit greater psychosis traits. In the present thesis, Experiment 4.1 sought to conceptually replicate this finding, by asking participants to memorise the colours of objects. In addition, I sought to extend the investigation to other perceptual features by exploring whether lower precision with which people remember either location or orientation features of objects is associated with greater psychosis traits. Altogether, Experiment 4.1 sought to test whether less precise features of remembered objects (i.e., colour, location, and orientation) are associated with greater psychosis traits.

To measure vividness of recollection, Experiment 4.1 adapted a vividness rating task that has been used in a previous study on precision of recollection (Richter et al., 2016). In Richter et al.'s study, participants were asked to first study a series of displays with objects overlaid on a background. In the later memory test phase, participants were presented with only the background and asked to rate, on a 100-point scale, how vividly they remembered the whole display, including the objects that had been studied with the tested background. This task provided a measure of subjective vividness with which participants remembered the displays.

To test whether qualities of memory might be associated with psychosis traits, Experiment 4.1 included two self-report scales of psychosis traits that have been often used to investigate possible links between qualities of mental experiences and psychosis traits. The first scale known as the 'Brief Oxford-Liverpool Inventory of Feelings and Experiences' has been described to measure both behavioural and personality traits often observed among schizophrenic patients (Chapman et al., 1995; Fernyhough et al., 2008). These traits known as 'schizotypy' include two sub-scales: inability to feel pleasure or 'Introvertive Anhedonia', and 'Unusual Experiences' (Claridge et al., 1996). The second scale known as the 'Modified Launay-Slade Hallucination Scale Revised' has been often used to measure proneness to hallucinations (Launay & Slade, 1981; Morrison et al., 2000). This scale measures participants' experience of vivid mental events (e.g., 'Sometimes my thoughts seem as real as actual events in my life'), hallucinations with a religious theme (e.g., 'In the past, I have heard the voice of the Devil'), and both auditory and visual hallucinatory experiences (e.g., 'I hear a voice speaking my thoughts aloud', 'On occasions, I have seen a person's face in front of me when no-one was in fact there') (Waters et al., 2003). Taken together, each participants' scores on these self-report scales may reflect their extent of schizotypy and proneness to hallucinations, collectively providing measures of psychosis traits.

Overall, Experiment 4.1 sought to investigate a notion from the '*psychosis continuum model*', that some healthy people may exhibit cognitive profiles that resemble those often observed among schizophrenic patients. These cognitive profiles may be linked, for example, where both lower precision and greater vividness of recollection may reduce the ability to keep track of reality, manifesting psychosis traits. To investigate these possible links, Experiment 4.1 tested whether both precision and vividness of recollection tend to be associated with psychosis traits, including schizotypy and proneness to hallucinations.

Methods

Participants

One hundred and sixty young adults between 18 to 35 years of age were included in the analysis. Two additional volunteers were excluded: one volunteer was excluded for exceeding the time allocated to complete the practice task (i.e. 40 minutes); the other volunteer withdrew from the study due to a headache, which was not caused by the current experiment. All participants reported normal vision, no history of psychiatric conditions, and provided informed consent according to the procedure approved by the University of Cambridge Human Biology Research Ethics Committee.

Stimuli & Materials

The stimuli in the precision memory task were 46 displays, each with 3 unique real-world objects overlaid on a faint patterned background. The colours of the objects were randomly selected from colour values ranging between 1-360 evenly distributed in the Commission Internationale de I'Eclairage L* (lightness) a* (red/green coordinates) b* (yellow/blue coordinates) colour space. The location and orientation features of objects were randomly selected from angles around a circle (i.e., 1-360º). A minimum distance of 62 degrees between objects was enforced to prevent the objects overlapping (Richter et al., 2016). The object-background combinations of the displays were randomly generated once, so all participants studied identical displays. The display presentation order was randomised for each participant.

Two self-report scales were used to measure traits of psychosis. The scale used to measure schizotypy, namely the 'Brief Oxford-Liverpool Inventory of Feelings and Experiences' (Brief O-LIFE), included 30 yes-or-no items (Fernyhough et al., 2008). These items were equally divided into two sub-scales: unusual experiences or 'positive schizotypy'; and introvertive anhedonia or 'negative schizotypy'. To catch possible inattentive responses to these scales, the scores for some of these items were reversed: the standard items were scored 1 for 'Yes' and 0 for 'No', whereas the reverse items were scored 1 for 'No' and 0 for 'Yes' (specified in Appendix A). Internal reliability of sub-scales in the Brief O-LIFE were good (α >= 0.7), whereas the factor loadings were not reported in the validation study (Fernyhough et al., 2008). Factor loading of these sub-scales may be similar to those in the original O-LIFE, where four factors accounted for a satisfactory, albeit low, portion of variance (24.7%) (Mason et al., 1995). The scale used to measure proneness to hallucination, namely the 'Modified Launay-Slade Hallucination Scale Revised' (LSHS-R), included 16 items

(Morrison et al., 2000). These items were scored on a Likert scale ranging from 0 (‘Never’) to 4 (‘Almost Always’). Internal reliability of sub-scales in the LSHS-R were good ($\alpha >= 0.64$), and two factors (i.e., auditory or visual hallucinations) explained a satisfactory, albeit low, portion of variance (38%). Greater scores on these scales indicated a greater extent of schizotypy and proneness to hallucination, respectively.

Procedures

All participants in Experiment 4.1 were tested in person. I tested 120 participants, and two undergraduate research students (i.e., Ana Tew and Laura Woodrow) collectively tested 40 participants. The stimuli were presented on a computer screen, using Psychtoolbox (version 3.0.13) and Matlab (version 2016b). Participants were first asked to complete both the schizotypy and proneness to hallucination self-report scales. Participants were then asked to complete the precision memory task, which consisted of 10 study-test cycles.

At the beginning of each study phase, a text prompt indicating both the study phase and the current study-test cycle number was presented (for 10s). This prompt was followed by sequential presentation of 4 displays (which lasted for 12s each). The displays were separated by a fixation cross (which lasted between 400-2500ms). Participants were asked to memorise all aspects of the displays, including the background, the objects, and the features of the objects (i.e. colour, orientation, and location).

At the beginning of each test phase, a text prompt indicating both the test phase and the current study-test cycle number was presented (10s). During this presentation, to minimise rehearsal of the studied displays, participants were asked to perform a simple arithmetic task: continuously subtracting a random number (ranging between 2 to 11) from the number 100. At the beginning of each test phase trial, participants were presented with just the background of a studied display (8s). After 2s following the onset of the background, participants were asked to rate ‘How vividly do you remember this display?’ on a 100-point continuous vividness slider, where 0 and 100 represented ‘not vividly’ and ‘very vividly’, respectively (within 6s). After the vividness rating, participants were asked to recreate, in a randomised sequence, features of two randomly selected objects in each display. Participants were presented with a studied object at a random location around a circle along with a cue in the middle of the circle indicating which feature participants should recreate for the respective trial (e.g., ‘colour’, ‘location’, ‘orientation’). To recreate the feature, participants were asked to move the object around the circle, by pressing the left and right arrow keys respectively, and press the spacebar to confirm their response (within 6s of the onset of the object). If participants did not make a response within the first 4s, the cue turned red to warn participants that they had 2s left to confirm their response. After the warning period expired, the respective trial terminated. Trials were separated by a fixation cross (which lasted between 400-2500ms). See Figure 4.1 for an overview of the task.

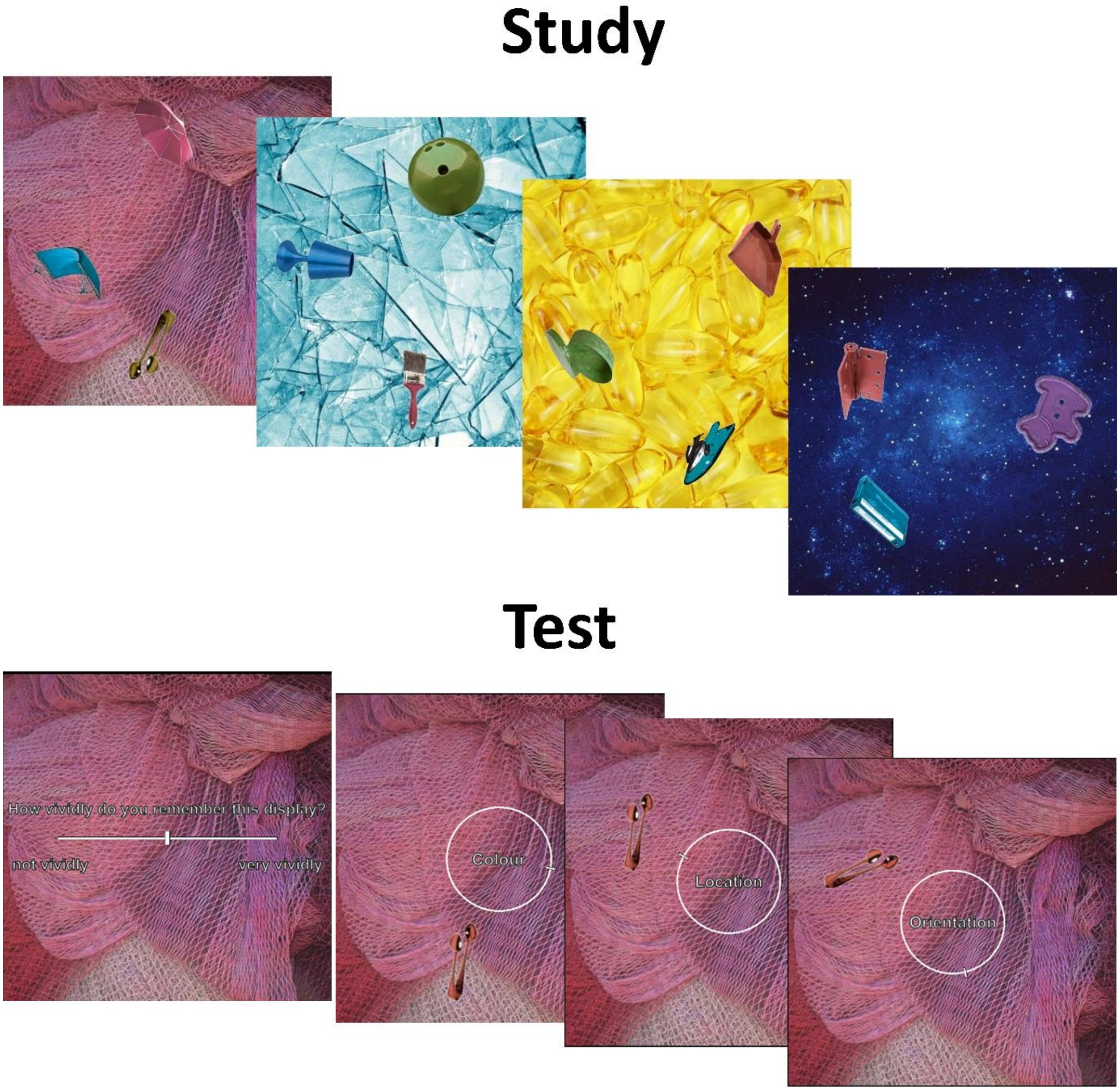

Figure 4.1. Precision Memory Task in Experiment 4.1. During the study phase, Participants were asked to study displays consisting of three unique objects, each with variable features (i.e., colour, location, and orientation). During the test phase, participants were first presented

with just the background and asked to rate vividness with which they remember the display. After the vividness rating, participants were asked to recreate features of object.

Analysis Approach

Experiment 4.1 sought to estimate the precision with which each participant remembered features of objects. The angle at which participants recreated features was subtracted from the angle of actual features, providing a measure of angular errors (in degrees). These errors could have reflected responses based on either recollection or random guesses. To distinguish these different types of responses, angular errors were used to generate a probabilistic mixture model consisting of two different types of distributions: a circular normal or ‘Von Mises’ distribution that reflects the overall precision of recollection; and a uniform distribution that reflects the proportion of successfully (or unsuccessfully) recollected trials (Bays et al., 2009; Zhang & Luck, 2008). This model provided an estimation of the precision with which each participant remembered features of objects denoted as ‘Kappa’. The same estimation approach was used to calculate separate recollection precision Kappa scores for each feature (i.e., colour, location, and orientation). Vividness ratings ranged between 0-100, the schizotypy self-report scale was scored out of 30 points, and the proneness to hallucination scale was scored out of 64 points. Descriptive statistics of these measures are reported in Table 4.1.

Statistical power analysis in Experiment 4.1 aimed to estimate the number of participants needed to detect a possible correlation, between a measure of mnemonic quality and a measures of traits of psychosis. This power analysis revealed that 133 participants were needed to detect a correlation similar to one observed in Xie and colleagues (2018) (r = .24, α = 0.05, $1\text{-}\beta$ = 0.8). A total of 160 participants were recruited, however, because I had collected 120 participants by the time the undergraduate research student started their data collection, and each student had to recruit at least 20 participants for their research projects (r = .24, α = 0.05, $1\text{-}\beta$ = 0.868). This power analysis was conducted in R, using the ‘pwr.f2.test’ function in the ‘pwr’ package. The main analyses in the current chapter estimated correlation coefficients, by using the ‘cor.test’ function built into the computer language ‘R’.

Table 4.1. Descriptive statistics in Experiment 4.1 as compared with the total psychosis traits scores in Xie et al. (2018).

	Precision of Recollection Kappa	**Vividness Ratings**	**Schizotypy Scores**	**Proneness to Hallucination Scores**	**Xie et al. 2018**
Mean (Standard Error)	8.598 (0.279)	48.656 (1.896)	6.594 (0.334)	13.138 (0.644)	8.95 (0.481)
Coefficient of Variability	0.411	0.495	0.64	0.609	0.688
Skewness	0.256	0.148	0.516	0.583	N/A
Normality *W*	0.986	0.98*	0.955***	0.957***	N/A

Note. 'N/A' = Not Available. Skewness score less than -1 or greater than 1, between -1 and 0.5 or 0.5 and 1, and between -0.5 and 0.5 indicates high, moderate, and no substantial skew, respectively. '*' = $p < 0.05$, '**' = $p < 0.01$, '***' = $p < 0.001$.

Results

Individual Differences

Testing whether qualities of recollection tend to be associated with psychosis traits requires participants to have exhibited individual differences in these measures, so that the qualities of recollection may be compared between participants with greater psychosis traits, relative to those with lower psychosis traits. One way to assess the extent of individual differences is to compare the dispersion of such measures in the current Experiment 4.1 with those in a previous study that did observe an association between precision of memory and traits of psychosis (Xie et al., 2018). Initial analysis first calculated standard deviations and, to adjust for possible differences in relative dispersions between studies, standard deviations were divided by the respective sample mean. Estimates of central tendencies such as the mean, however, often involves margins of error, so the standard deviations were also divided by both the upper and the lower 95% confidence intervals of the mean. This calculation yielded an estimate of dispersion known as 'coefficient of variability' and its margin of error (Morse, 1993), enabling a comparison of dispersions between measures in Experiment 4.1 and those in Xie et al.. The error margins of the coefficient of variability overlapped and, therefore, coefficient of variability were comparable between the total schizotypy score in Xie et al. (0.623-0.769) and both measures of schizotypy (0.583-0.711) and proneness to hallucinations (0.556-0.672) in the current experiment.

Standardised measures of dispersion such as the coefficient of variability may, however, overestimate the extent of sample dispersion, if the sample tends to be skewed. Skewness is, of course, not a measures of variance; it assesses whether or not samples are concentrated on either ends of the scales of measurements. If the sample is indeed skewed, however, a small number of observations can bias standardised measures of dispersion to overestimate sample variance and, therefore, variance should be interpreted in mind of possible confounds, such as skewness. Estimation of skewness revealed that both psychosis trait scores were moderately skewed towards the lower end of the respective scales, suggesting that individual differences in psychosis trait scores may be moderately overestimated (see Table 4.1 for the statistics). In contrast, no substantial skew was observed in qualities of recollection, suggesting that individual differences in recollection precision Kappa scores and vividness ratings may be relatively less biased by skewed samples.

Even if no substantial skew was observed, however, abnormal distributions (such as binomial distributions) may bias estimates of dispersions. Shapiro-Wilk tests were conducted to test the normality of all measures. Only the recollection precision Kappa scores were normally distributed, suggesting that individuals differences in precision of recollection may be less biased than other measures, including the vividness ratings.

In light of such different characteristics of samples in different measures, all measures were scaled using the ‘scale’ function in R, so that possible irregularities may be reduced between these measures.

Associations Between Qualities of Recollection and Psychosis Trait Scores

The main analysis sought to test whether participants that tend to exhibit generally lower precision of recollection tend to also exhibit greater psychosis traits. Pearson’s correlations may help to reveal subtle associations, as they preserve the sensitivity of continuous measures, such as the precision of recollection Kappa scores. Pearson’s correlations can be, however, too sensitive to outliers especially when characteristics of samples between measures tend to be different, resulting in possibly biased estimates. In contrast, Spearman’s Rho first ranks the measures, so it is less susceptible to characteristic differences between measures, providing possibly less biased estimates of associations, although it may be less sensitive than Pearson's correlations. To complement these pros and cons of Pearson's and Spearman's correlation tests, both approaches were used to estimate possible associations between precision of recollection Kappa and either schizotypy scores or proneness to hallucination scores.

Both approaches to testing for this possible association, however, did not reveal significant correlations ($r <= 0.065$, $p >= 0.412$; $r_s <= 0.041$, $p >= 0.608$). This possible association was also not observed between precision of recollection Kappa in each feature (i.e., colour, location, and orientation) and sub-scales of schizotypy scores (i.e., unusual experiences scores and introvertive anhedonia scores) ($r <= 0.139$, $p >= 0.079$; $r_s <= 0.1$, $p >= 0.207$), or between precision of recollection Kappa in each feature and proneness to hallucination scores ($r <= 0.076$, $p >= 0.339$; $r_s <= 0.069$, $p >= 0.387$).

Subsequent analysis sought to test whether greater vividness of recollection tends to be associated with greater psychosis traits. Testing for this possible association, between vividness ratings and either the schizotypy scores and proneness to hallucination scores, did not reveal significant correlations ($r <= 0.133$, $p >= 0.093$; $r_s <= 0.128$, $p >= 0.106$). This association was also not observed between vividness ratings and both scores on sub-scales of schizotypy ($r <= 0.021$, $p >= 0.79$; $r_s <= 0.226$, $p >= 0.777$).

Discussion

Experiment 4.1 sought to investigate a notion the stems from the psychosis continuum model: qualities of recollection may be associated with psychosis traits among healthy people. If participants exhibited less precise qualities of recollection, for example, participants might have been more likely to misattribute imagined events as being real, resulting in greater psychosis traits. If participants also exhibited more vivid qualities of recollection, even when their precision of recollection tended to be lower for example, this might also have had an effect on participants' psychosis traits. Inconsistent with these predictions, however, Experiment 4.1 did not observe any significant association between qualities of recollection and psychosis traits. These findings are inconsistent with findings from a previous study that did observe a significant link between precision of memory and psychosis traits (Xie et al., 2018). Therefore, evidence remains mixed for a possible association between mnemonic qualities and psychosis traits.

This mixed evidence may be partly due to insufficient individual differences in both the qualities of recollection and psychosis traits in the present data. For example, participants' scores on the psychosis trait scales were often skewed towards the lower end of the scale, suggesting that standardised estimates of dispersion might have overestimated individual differences in psychosis traits. To investigate a possible link between qualities of recollection and psychosis traits, however, participants must have first exhibited a sufficient extent of individual differences in both qualities of recollection and psychosis traits, so that the qualities of recollection may be compared between participants that tended to exhibit greater psychosis traits, relative to those that exhibited less psychosis traits. So lack of variances in measures of psychosis trait scores may have induced a floor effect.

The limited individual differences in psychosis traits observed in Experiment 4.1 might perhaps be due to the self-report scales on psychosis traits used. The validity of the Brief O-LIFE used to measure schizotypy, for example, stems from the original O-LIFE, which may lend some support for the notion that the brief version may indeed measure schizotypy (Chapman et al., 1995). However, validity of the Brief O-LIFE remains largely unknown, because the data that was used to validate the scale has not been published (Fernyhough et al., 2008). Future studies may need to not only validate Brief O-LIFE but also report the evidence of the validation, so that subsequent studies may assess whether this scale may be valid for the respective research aims. Alternately, a future study may incorporate a scale of schizotypy that has already been validated, in a large sample of healthy people, which may help to reveal a currently elusive link between qualities of recollection and schizotypy. Moving on to the 'Modified Launay-Slade Hallucination Scale Revised' used to measure proneness to hallucination, items in this scale often concern multiple kinds of hallucinatory experiences, so participants' responses to these items may have been mixed. For example, some of the items concern both perceptual and religious hallucinatory experiences (e.g., 'I have heard the voice of the Devil'), and participants that experience only either one of these kinds of experiences may indicate that such items do not apply to them. So participants may have scored generally lower, even when some of the participants did indeed experience at last one kind of hallucinatory experiences. So using a scale that can measure more specific aspects of hallucinations may help to tease apart the kinds of participants' hallucinatory experiences. Such scales may capture a greater extent of individual differences in participants' hallucinatory experiences, relative to the scales used in Experiment 4.1, helping further studies to investigate a possible link between qualities of recollection and hallucinatory experiences.

Altogether, results from Experiment 4.1 have provided limited support for the notion that qualities of recollection may be associated with psychosis traits. To further investigate this possible association, it may be that a greater extent of individual differences needs to be observed in both the qualities of recollection and psychosis traits. The precision of recollection, for example, tended to be dispersed without a substantial skew or abnormal distribution in Experiment 4.1, so a further investigation may benefit from including a similar measure of the quality of recollection. Also including more robust scales of psychosis traits, relative to ones used in Experiment 4.1, may help a further study to investigate whether precision of recollection tends to be associated with psychosis traits.

Experiment 4.2: Introduction

Experiment 4.2 sought to further investigate a possible association between precision of recollection and psychosis traits. Lower precision with which we remember our own actions and imagined experiences, known as internally-generated information, may induce misattribution of this information to another person or external environments, known as externally generated information (see Chapter 2). A tendency to commit such misattributions may result in externalisation biases often observed in patients with schizophrenia, especially in patients that tend to experience hallucinations (Simons et al., 2017). Taken together, these views suggest that lower precision of recollection concerning internally generated information may be associated with greater psychosis traits. According to the psychosis continuum model, this possible association may be observable among healthy people. Experiment 4.2 sought to test this notion, that healthy people with generally lower precision of recollection especially concerning internally generated information may exhibit greater psychosis traits.

To first estimate the precision of recollection, Experiment 4.2 re-analysed the data from the behavioural experiments in Chapter 2. In Experiment 2.1, participants were asked to either progressively move an object to a location around a circle, or watch the object being moved by the experimenter; whereas participants in Experiment 2.2 were asked to either imagine or perceive an object progressively moving to a location around a circle. In both Experiments 2.1 and 2.2, participants were asked to recreate the precise location of each object. Participants' responses on these tasks were used to generate mixture models that can distinguish responses based on recollection, rather than random guesses, providing an estimate of the precision of recollection Kappa (Bays et al., 2009; Zhang & Luck, 2008). These mixture models were used to estimate the precision with which participants remembered distinguishable types of information: internally-generated information, which includes self-generated actions and mental imagery; and externally-generated information, which includes other-generated actions and perceived events.

To test whether precision of recollection concerning internally generated information tends to be associate with psychosis traits, relative to those concerning externally generated information, Experiment 4.2 sought to estimate psychosis traits among participants in Experiments in 2.1 and 2.2. All participants were asked to complete two self-report scale measures of psychosis traits. The first scale known as the ‘Schizotypal Personality Questionnaire Brief Revised Updated’ can be used to measure schizotypal personality often observed in patients with schizophrenia (Davidson et al., 2016). Crucially, this schizotypal personality scale has been both validated and reported, unlike the Brief O-LIFE that was used to estimate schizotypy in Experiment 4.1. The second scale known as the ‘Cardiff Anomalous Perception Scale’ can be used to measure people’s tendency to experience hallucinations concerning anomalous perceptions (Bell et al., 2006). This scale may estimate the participants’ proneness to specific hallucinatory experiences concerning anomalous perceptions, unlike the LSHS-R used in Experiment 4.1 which may estimate proneness to multiple kinds of hallucination.

Experiment 4.2 sought to investigate whether the precision of recollection concerning internally relative to externally generated information tends to be associated with psychosis traits, including both schizotypal personality and anomalous perceptions. Participants with lower precision of recollection concerning internally generated information were expected to exhibit greater psychosis traits.

Methods

Participants

Participants included in the analysis of Experiment 4.2 were those of Experiments 2.1 and 2.2. Forty-eight young adults, between 18 to 35 years of age, participated in each Experiment 2.1 and 2.2, totalling 96 participants overall. One outlier’s scores on psychosis traits self-report scales were at least 3 standard deviations greater than the mean scores across participants. This outlier was removed, so a total of 95 participants were included in the final analysis of Experiment 4.2. All participants reported normal or corrected-to-normal vision and hearing, and no history of psychiatric or neurological conditions. Participants provided informed consent in accordance with the procedure approved by the University of Cambridge Human Biology Research Ethics Committee.

Materials

The 'Schizotypal Personality Questionnaire Brief Revised Updated' consisted of 32 items concerning four aspects of schizotypy: difficulties with interacting with other people or 'interpersonal', a tendency to experience anxiety in social situations or 'social anxiety', a tendency to engage in magical thinking and experience unusual perceptions or 'cognitive-perceptual', and eccentric behaviour and odd speech or 'disorganised' (Davidson et al., 2016). Responses to these items were scored on a five-point scale, where '1' represents 'strongly disagree' and '5' represents 'strongly agree'. Greater scores across these items indicated greater schizotypal personality. Internal reliability of sub-scales in this schizotypal personality questionnaire were good (ω >= 0.686), and four factors (i.e., the sub-scales) explained a moderate portion of variance (41%) (Davidson et al., 2016).

The 'Cardiff Anomalous Perception Scale' consisted of 32 items concerning three kinds of hallucinatory experiences (Bell et al., 2006). The first component was associated with illusions and hallucinatory experiences often observed in patients with temporal lobe epilepsy or 'temporal lobe experience' (Gloor, 1990). The second component largely concerned unusual olfactory and gustatory experiences or 'chemosensation'. The third component was associated with pathological anomalous perceptions often used as indicators of schizophrenia or 'clinical psychosis'. These items first required a 'yes' or 'no' response, and only if the initial response was 'yes', subsequent responses were scored on a five-point Likert scale, where scores of 1 and 5 represented 'not distressing at all' and '5' represents 'very distressing', respectively. Greater scores across these items indicated greater proneness to anomalous perceptions. Internal reliability of the CAPS was good (α = 0.87), and three factors (i.e., the sub-scales) explained a satisfactory, albeit low, portion of variance (33.07%) (Bell et al., 2006).

Stimuli and Procedures

Experiment 4.2 re-analysed the data from Experiments 2.1 and 2.2, so the stimuli and procedures in Experiments 2.1 and 2.2 are reiterated below.

Each display consisted of an image of a real-world object overlaid on a faint patterned background. A total of 360 displays were used. The following variables were randomly allocated between participants: the pairing of objects with backgrounds, object target locations around a circular space between 1-360°, displays in each reality condition (i.e., 'self', 'experimenter', 'imagined', and 'perceived'), and display presentation order within each study-test cycle. The displays were identical between participants, but the display presentation order was different for each participant.

In Experiment 2.1, participants completed a practice phase followed by 7 study-test cycles. Each cycle consisted of 24 displays, half of which were in the 'self' condition, and the other half were in the 'experimenter' condition.

In each study phase trial, we presented a cue (lasting 1s), which indicated whether the self (i.e., the participant) or the experimenter was to move the object that was subsequently presented in the middle of the computer screen. In the 'self' condition, participants were asked to hold down the spacebar on a keyboard to move the object progressively to its target location, whereas in the 'experimenter' condition, participants were asked to watch the object move progressively to its target location as the experimenter held down the 'Q' key (within 3s of the object being presented). When the object reached its target location, participants were asked to think about what the object was, where its target location was, and whether they themselves or the experimenter moved the object (3s).

In each test phase trial, we presented a series of studied objects at random locations around a circular space. Participants were asked to first recreate the target location of each object by holding down the left and right arrow keys, which moved the object anti-clockwise and clockwise around the circular space, respectively. Participants were also asked to decide whether the object had been moved by they themselves or the experimenter during the preceding study phase by pressing the 'S' and 'E' keys, respectively. The trials were subject paced, terminating if participants did not respond after 9s. We presented a text reminder of what each key represented in the middle of the computer screen, which turned red to indicate when 3s was left before the trial expired.

In Experiment 2.2, participants completed a practice phase followed by 10 study-test cycles. Each cycle consisted of 18 displays, half of which were in the 'imagined' condition, and the other half were in the 'perceived' condition. We used fewer displays for each study-test cycle in experiment 2 (i.e., 18 displays) relative to experiment 1 (i.e., 24 displays) to prevent floor effects that emerged in pilot testing of this experiment.

In each study phase trial, we presented an object in the centre of the computer screen (3s). In the ‘imagined’ condition, the object was replaced by a black cross, and participants were asked to imagine the object moving progressively to the target location as the cross moved progressively to the target location (1s). In the ‘perceived’ condition, participants were asked to watch the object move progressively to its target location (1s). When the cross or the object reached its target location, participants were asked to think about what the object was, where its target location was, and whether the movement of the object was imagined or perceived (3s).

The test phase of experiment 2 was identical to the test phase of experiment 1, except that participants were asked to press the ‘I’ and ‘P’ keys to indicate whether the object had been imagined or perceived during the preceding study phase, respectively.

Analysis Approach

To estimate the precision of recollection, as in Experiment 4.1, angular errors were used to generate mixture models, which provided the precise of recollection Kappa. (Bays et al., 2009; Zhang & Luck, 2008). A similar modelling approach was used to estimate the precision of recollection Kappa in ‘self’, ‘experimenter’, ‘imagined’, and ‘perceived’ reality conditions. Both self-report scales on schizotypal personality and anomalous perception were scored out of 160 points.

Statistical power analysis in the previous Experiment 4.1 suggested that 133 participants might be required to observe a correlation similar to one observed in Xie and colleagues (2018) (r = .24), but the main analysis in Experiment 4.1 did not reveal any significant correlation, despite its large sample size (n = 160), suggesting that the correlation observed in Xie and colleagues (2018) might not necessarily inform statistical power analysis in similar experiments. The power analysis in Experiment 4.2, therefore, aimed to estimate the number of participants needed to detect a standard medium-size correlation (r = .3), rather than one observed in Xie and colleagues (2018). This power analysis revealed that 84 participants were needed to detect a medium correlation ($\alpha = 0.05$, $1\text{-}\beta = 0.8$). Note, however, that Experiment 4.2 re-analysed data from Experiments 2.1 and 2.2, where each experiment recruited 48 participants and, therefore, a total of 96 participants were included in the main analyses (r = .3, $\alpha = 0.05$, $1\text{-}\beta = 0.851$). This power analysis was conducted in R, using the ‘pwr.f2.test’ function in the ‘pwr’ package. The main analysis in the current chapter estimated correlation coefficients using the ‘cor.test’ function built into the computer language ‘R’.

Results

Individual Differences

As in Experiment 4.1, the initial analysis sought to test whether participants exhibited individual differences in precision of recollection Kappa scores, schizotypal personality scores, and anomalous perceptions scores. The error margins of the coefficient of variability observed in the current Experiment 4.2, including those of both schizotypal personality scores (0.245-0.272) and anomalous perceptions scores (0.845-1.28), did not overlap with those observed in Experiment 4.1 concerning measures of schizotypy (0.583-0.711) and proneness to hallucinations (0.556-0.672), or those observed in Xie et al (0.623-0.769). Notably, no substantial skew was observed in schizotypal personality scores, whereas anomalous perceptions scores tended to be highly skewed towards the lower end of the scale, suggesting that its coefficient of variability might reflect overestimated individual differences in anomalous perception scores (see Table 4.2 for descriptive statistics). To minimise possible irregularities in the scores on these self-report scales and the precision of recollection Kappa, all measures were scaled using the ‘scale’ function in ‘standardize’ package in R.

Table 4.2. Descriptive statistics in Experiment 4.2.

	Precision of Recollection Kappa	**Schizotypal Personality Scores**	**Anomalous Perceptions Scores**
Mean	18.163	42.503	10.209
(Standard Error)	0.873	3.217	1.106
Coefficient of Variability	0.467	0.258	1.018
Skewness	0.418	-0.273	1.357
Normality *W*	0.976	0.985	0.842***

Note. Skewness score less than -1 or greater than 1, between -1 and 0.5 or 0.5 and 1, and between -0.5 and 0.5 indicates high, moderate, and no substantial skew, respectively. ‘*’ = $p < 0.05$, ‘**’ = $p < 0.01$, ‘***’ = $p < 0.001$.

Association Between Precision of Recollection and Psychosis Trait Scores

The main analysis sought to test whether precision of recollection was associated with schizotypal personality and the anomalous perception. Both Pearson's and Spearman's correlations testing for these possible associations revealed a significant positive association between precision of recollection Kappa scores and schizotypal personality scores ($r = 0.228$, $p = 0.026$; $r_S = 0.248$, $p = 0.015$). In contrast, no such association was observed with the anomalous perception scores ($r = -0.053$, $p = 0.611$; $r_S = 0.041$, $p = 0.692$). Conducting these four correlation tests might have increased the likelihood of observing false positive results, so the alpha was corrected for the number of comparisons ($\alpha = 0.013$). Upon multiple comparison correction, only a trend towards a significant positive association was observed between precision of recollection Kappa scores and schizotypal personality scores.

Follow-up correlations sought to test whether the precision of recollection concerning internally and externally generated information was associated with scores on the sub-scales of the schizotypal personality scale (i.e., 'interpersonal', 'social anxiety', 'cognitive-perceptual', 'disorganised') ($\alpha = 0.003$). These tests did not reveal any significant associations ($r = 0.153$, $p >= 0.14$; $r_S <= 0.164$, $p >= 0.111$).

Discussion

Experiment 4.2 sought to test whether the precision with which people remember past events may be associated with psychosis traits. This view was tested by first asking participants to complete precision memory tasks that can distinguish internally and externally generated information, and then exploring whether participants' precision of recollection in these tasks tends to be associated with scores on self-report scales that can measure psychosis traits, including schizotypal personality and anomalous perception. It was postulated that people with lower precision of recollection may struggle to keep track of the original sources of memory, inducing confusions between imagined and real experiences. Lower precision of recollection especially concerning internally generated information, such as our actions and imagined experience, could have induced a bias, characterised by a tendency to misattribute internally generated information to external sources, such as actions of other people or perception of the outside world. People with such externalisation biases may have manifested greater psychosis traits. So it seemed reasonable that lower precision of recollection may be associated with greater psychosis traits, especially in circumstances where the contents of the memory concerned internally relative to externally generated information. In contrast to this view, however, Experiment 4.2 observed that participants with greater precision of recollection tended to exhibit greater scores on schizotypal personality scale (albeit a result that did not survive correction for multiple comparisons), suggesting a positive association between precision of recollection and psychosis traits.

Such positive associations between precision of recollection and psychosis traits are, at least in part, inconsistent with previous findings that reduced qualities of mental experiences may be associated with greater traits of clinical psychosis. Previous research involving patients with schizophrenia, for example, observed patients often exhibit lower reality monitoring performance relative to healthy people, suggesting that patients' mnemonic qualities may be atypical (see Simons et al (2017) for a review). According to the psychosis continuum model, such an association between qualities of recollection and psychosis traits may manifest among some healthy people (Meehl, 1962). So people with better qualities of recollection, for example, may be more likely to be able to distinguish real and imagined information and, therefore, exhibit fewer psychosis traits. In the current study, however, greater precision of recollection was associated with greater schizotypal personality traits (noting the caveat concerning multiple comparisons correction), suggesting that people with better qualities of recollection, and thus greater reality monitoring performance, might have tended to exhibit greater schizotypy.

One possible account for these data could be that people with better qualities of memory might exhibit greater schizotypy, if the contents of memory tend to rich and vivid. In line with this view, studies that investigated vividness of imagined experiences in multiple groups of people with varying extents of schizotypy, for example, observed that patients with schizophrenia, their first degree relatives, and healthy people with greater schizotypy tend to exhibit greater vividness of mental imagery, relative to healthy people with lower schizopy (Oertel et al., 2009). So better qualities of mnemonic representations may be associated with schizotypy.

Specific associations remain unclear, however, between the precision of recollection and different types of schizotypal traits, such as interpersonal social anxiety, unusual cognitive-perceptual experiences, and disorganised behaviours. If, for example, mental representations tend to be more vivid among people on the greater end of the schizotypy spectrum (Oertel et al., 2009), and their precision of recollection is intact (Bays, 2010), it is possible that people with specific schizotypy, such as heightened interpersonal social anxiety, may first generate vivid simulations of future social events, so that they may remember precise details of these episodic simulations, thereby anticipating possibly anxiety-provoking social events (Schacter & Addis, 2007). Such specific associations have not been observed, however, in both the current Experiment 4.2 and a similar study that investigated a possible association between reality monitoring performance and psychosis traits among a larger sample of healthy people (N = 1394) (Moseley et al., 2020), suggesting that even greater statistical power may be limited in testing possible associations between qualities of recollection and psychosis traits.

This lack of replication raises a concern about the reliability of previous findings, where precision of recollection tended to be lower in both people with greater schizotypy (Xie et al., 2018) and schizophrenic patients (Gold et al., 2010). These previous findings may, for example, warrant further investigation due to a few caveats in these studies. The study by Xie et al. involving healthy people conducted multiple statistical tests, which may increase the probability of observing false positive results, and – like in the present experiment - their statistical results would not have survived multiple comparison corrections often used to reduce the likelihood of false positive results. So their findings, consistent with those of the current study, suggests that limited evidence remains for a possible link between precision of recollection and schizotypy. Turning to the study by Gold et al. that measured the precision of recollection among patients with schizophrenia, they used four-alternative choice recall task, unlike a precision memory paradigm that can measure precision of recollection on a continuous scale, so their experimental task may have been limited in measuring precision of recollection. Their task may have instead captured a greater guessing rate among patients with schizophrenia, relative to healthy controls (Bays, 2010). So a possible link between the precision of recollection and psychosis traits in patients with schizophrenia remains elusive.

A similar link also remains elusive between the precision of recollection and anomalous perception or hallucinations. Participants in the current experiment tended to score on the lower end of the anomalous perception scale, suggesting a possible floor effect. To investigate whether healthy people may exhibit traits associated with clinical psychosis, such as worse qualities of mental representations and hallucinations, future studies may benefit from developing a more sensitive measure that can capture some extent of variability with which healthy people may experience hallucinations. One such possible measure may involve inducing hallucinations, so that researchers may explore whether precision of recollection may be associated with proneness to induced hallucinations (Powers et al., 2017).

Experiment 4.2 revealed that greater precision with which people remember past experiences was associated with schizotypy; whereas no such association was observed with participants' tendency to experience anomalous perceptions. This lack of association may be due to a possible floor effect, where people generally score on the lower end on scales that measure anomalous perceptions or hallucinations. These findings are inconsistent with a notion that stems from the psychosis continuum model, that healthy people may exhibit cognitive profiles often associated with clinical psychosis, such as worse qualities of recollection and hallucinatory experiences.

Chapter 5: General Discussion

Experiments reported in the current thesis sought to investigate how we may keep track of reality, by testing the key notion from the 'Source Monitoring Framework': reality monitoring decisions may depend on qualitative characteristics of underlying mnemonic representations, such as the precision with which we remember visuoperceptual details of past personal experiences (Johnson et al., 1993). This postulation was, by and large, supported by results from the experiments reported in this thesis that concern behavioural associations, neurocognitive evidence, cognitive manipulations, and individual differences analyses. On balance, these results suggests that multiple relationships may exist between reality monitoring decisions and underlying mnemonic qualities. These multiple relationships may be better described by a combination of previously separate theoretical accounts, including the Source Monitoring Framework (Johnson et al., 1993), the Fuzzy Trace Theory (Brainerd et al., 2008; Brainerd & Reyna, 1998), the guessing hypothesis (Bayen et al., 2000; Küppers & Bayen, 2014), and predictions regarding congruency and incongruency advantages (Greve et al., 2019; Sterzer et al., 2018; Van Kesteren et al., 2012); whereas any single theoretical account, such as the psychosis continuum model (Meehl, 1962), may not be sufficient to describe the multiple ways in which reality monitoring may depend on underlying mnemonic qualities. In light of these theoretical implications, the current Chapter 5 proposes a combined model that aims to account for the multiple relationships between qualities of mnemonic representation, reality monitoring decisions, and traits of psychosis.

Summary of Findings and Their Theoretical Implications

According to the Source Monitoring Framework, we may distinguish previously imagined and perceived experiences by considering the qualities of these mental experiences. We may, for example, consider that these qualities resemble those often associated with imagined experiences (Johnson et al., 1993; Johnson & Raye, 1981). Based on this resemblance, we may decide that those mental experiences resulted from past acts of imagination. When qualities of imagined experiences are clearly distinct from those associated with perceived experiences, we may easily be able to distinguish those imagined and perceived experiences, facilitating reality monitoring decisions. Building on this notion from the Source Monitoring Framework, behavioural experiments reported in chapter 2 of the current thesis sought to provide a novel insight, that the precision with which we remember details of past events may be one of the mnemonic qualities that may underlie reality monitoring decisions. To investigate whether reality monitoring decisions may indeed depend, at least in part, on memory precision, participants in these behavioural experiments were asked to remember precise visuoperceptual locations of objects and, in turn, make different types of classic reality monitoring decisions: ‘agency reality monitoring decisions’, which distinguish their past actions from those performed by another person; and ‘perceptual reality monitoring decisions’, which distinguish imagined and perceived experiences. These experiments revealed that performance on both agency and perceptual reality monitoring decisions tend to be better when the underlying mnemonic representation was more precise, suggesting that our ability to keep track of reality may indeed depend on precise qualities of mnemonic representations. These findings are consistent with the key notion from the Source Monitoring Framework, that we may keep track of reality by considering qualitative characteristics of mental experiences.

This link between reality monitoring decisions and memory precision may help us to understand some of the cognitive profiles often observed in people with psychosis. Reduced reality monitoring performance, for example, has been reliably observed in previous research involving patients with schizophrenia, suggesting that qualities of patients’ memory, which may underlie their reduced reality monitoring performance, may be different to those among healthy people (Simons et al., 2017). Previous research has, however, focused on measuring reality monitoring performance, rather than the quality of underlying mnemonic representations, so how these mnemonic qualities may be different between patients and healthy people remained unresolved. The finding from behavioural experiments in chapter 2, that worse reality monitoring performance tended to be associated with lower memory precision, implies that patients’ reality monitoring performance tends to be worse because their underlying memory representations are on average less precise, relative to healthy people.

Such relatively imprecise mnemonic representations may involve less of the typical qualities that distinguish them as our own, so lower memory precision may be associated with externalisation biases: for example, ‘agency externalisation bias’, a tendency to misattribute our past actions to another person; and ‘perceptual externalisation bias’, a tendency to misattribute imagined experiences to perceptions of the outside world. In line with this view, behavioural experiments in chapter 2 observed that participants were more likely to misattribute their past actions to another person, especially when the underlying memory precision tended to be lower; and participants’ tendency to misattribute imagined experiences, more than perceived experiences, tended to be associated with lower memory precision concerning imagined experiences, relative to those concerning perceived experiences. Interestingly, participants tended to misattribute imagined experiences more than perceived experiences when the underlying mnemonic representations of imagined experiences were unusually precise, suggesting that we may misattribute memories of imagined experiences that are more precise and vivid than usual as likely to be perceptions of the outside world, because perceptions often exhibit those kinds of qualities (Richter, 2020). While these observations collectively provide evidence for a previously elusive link between externalisation biases and memory precision, it also suggests that the way in which agency and perceptual externalisation biases are linked to memory precision may be different.

These links may help us to understand externalisation biases that have been reliably observed in previous research involving patients with schizophrenia who, as a prominent positive symptom in the majority of patients, tend to experience hallucinations (Simons et al., 2017). These patients may, for example, mistakenly believe that another person has moved an object when in fact, the patients themselves moved the object, possibly because their memory tends to be reduced in precision such that it contains fewer of the typical qualities, or less well defined examples of those qualities, that distinguish them as their own. Patients may also mistakenly say that they have seen objects move, which were not real, because qualities of their imagined experiences tend to resemble those more often associated with perceived experiences, such as rich and vivid visuoperceptual details. According to these views, agency externalisation biases may be associated with atypically imprecise qualities of mnemonic representations; whereas perceptual externalisation biases may be associated with unusually rich and vivid mnemonic qualities of imagined experiences.

While these links between externalisation biases and mnemonic qualities suggest that multiple kinds of relationships may exist between reality monitoring decisions and mnemonic qualities, these links do not reveal the direction of these relationships. The notion from the Source Monitoring Framework, that reality monitoring decisions depend on mnemonic qualities, for example, implies a possible sequence of cognitive processes, where we must first remember details of past events so that, in turn, we may decide the original source of these remembered experiences. If this notion is true, stimulation of a brain region that helps us to remember past experiences, such as angular gyrus, may first reduce qualities of our memory and, in turn, disrupt reality monitoring decisions, resulting in lower reality monitoring performance. Brain stimulation experiments in Chapter 2 sought to test whether stimulation of angular gyrus may first reduce memory precision and, in turn, disrupt both agency and perceptual reality monitoring performance, relative to stimulation of a control site. However, these studies did not observe the stimulation of angular gyrus to significantly affect memory precision, despite sufficient statistical power to detect such effects if they exist (34 samples were needed to detect a medium-sized effect with a statistical power of 0.8, and 48 samples were analysed in each Experiments 2.3 and 2.4). This lack of causal neurocognitive evidence allows a possibility, where angular gyrus may facilitate precise recollection under typical circumstances, but disruption of angular gyrus may induce other functionally connected regions to step in, resulting in apparently intact memory precision. Accordingly, a previous study that stimulated a functional connection between posterior parietal regions including angular gyrus and hippocampus observed increased memory precision, substantiating the notion that interconnected regions may step in to support precise recollection (Nilakantan et al., 2017). A functional neuroimaging study, however, observed an association between greater memory precision and stronger functional connections within the posterior medial network that includes angular gyrus, but no such connections were observed with other regions such as hippocampus (Cooper & Ritchey, 2019). Thus, the evidence suggests that angular gyrus and its neighbouring regions may be sufficient to support precise recollection in typical situations, without brain stimulation, and precise recollection may involve multiple interconnected brain regions, suggesting that reality monitoring decisions may depend on multiple neurocognitive bases of precise recollection.

Even though overall memory precision was intact in the brain stimulation experiments described in Chapter 2, however, stimulation of angular gyrus selectively reduced the link between self-referential reality monitoring decisions and the precision underlying mnemonic representations, relative to control site stimulation. This finding suggests that angular gyrus may be particularly important for imbuing our memory with self-agency, enabling a subjective sense of re-living our past, known as ‘autonoetic consciousness’, which characterises episodic memory (Tulving, 1985). In contrast, these experiments did not reveal a significant effect of angular gyrus stimulation on the relationship between perceptual reality monitoring decisions and the underlying memory precision, which might suggest that another brain region may be responsible for this relationship.

If one of these neurocognitive bases was disrupted and, therefore, mnemonic qualities such as autonoetic consciousness were reduced, participants may come to make reality monitoring decisions by considering other mnemonic qualities, such as those reflected in a schema that reflects common qualities of previous experiences, so that they can still distinguish real from imagined information. In line with this view, brain stimulation experiments in Chapter 2 observed that, even when participants' autonoetic consciousness may have been reduced, their agency reality monitoring performance remained intact, suggesting the possibility that participants kept track of reality by adapting strategies that may not require autonoetic consciousness, such as assessing the familiarity of mental representation. This finding suggests that reality monitoring decisions may adapt to depend on multiple qualities of mnemonic representations.

Such adaptations may be particularly apparent when we forget details of past events and, therefore, reality monitoring decisions cannot depend on precise qualities with which we remember past experiences. We may, for example, forget details of past experiences after a long delay period (e.g., 24 hours), relative to no delay. Consistent with this view, Experiment 3.1 reported in Chapter 3 observed that participants' ability to remember visuoperceptual locations of each object after a 24-hour delay period tended to be worse than immediately after respective study phases, suggesting that participants may have forgotten and, therefore, guessed the locations of objects. Even after 24 hours, however, participants were able to accurately indicate distinct visuoperceptual locations associated with either imagined and perceived experiences, indicating that the influence of schemas on performance was relatively preserved. At least in this situation, where participants may have forgotten precise details of past experiences, but their knowledge about common qualities of these experiences is intact, reality monitoring decisions might depend on whether qualities of mental experiences feel familiar. If, for example, qualities of multiple past experiences reflected in knowledge structures, such as schemas (Gilboa & Marlatte, 2017), are incongruent to those of a mental experience, participants might have experienced a sense that the mental experience is unfamiliar, helping them to accurately indicate that the mental experience was imagined. When the strength of schemas concerning imagined experiences tend to be weaker, the intensity of the sense of familiarity may have decreased, inducing externalisation bias observed in Experiment 3.2.

Collective findings from both Experiments 3.1 and 3.2 suggest that, when we can remember details of past experiences and, in turn, experience autonoetic consciousness which characterises episodic memory, reality monitoring decisions may depend on qualities associated with episodic memory; If, however, episodic memory is reduced, reality monitoring decisions may instead depend on sense of familiarity often associated with 'noetic consciousness', which characterises a schema and, more broadly, semantic memory (Tulving, 1983). So reality monitoring decisions may depend on mnemonic qualities associated with at least two different kinds of long-term memory systems: episodic and semantic memories.This broad description, that reality monitoring decisions may depend on multiple mnemonic qualities, may be compatible with theoretical accounts that provide an overarching framework with which we may research reality monitoring, such as the Source Monitoring Framework. However, the way in which reality monitoring decisions may depend on qualities associated with different long-term memory systems may be better understood using more specific theoretical accounts about long-term memory. According to one of such theoretical accounts known as the ‘Fuzzy Trace Theory’, we may forget precise details of past experiences and, therefore, we may instead retrieve imprecise or ‘fuzzy’ gist-like memory, such as those associated with a schema, which may induce a false sense that imagined experiences had actually happened (Brainerd et al., 2001). A related hypothesis known as the ‘guessing hypothesis’ adds that, if we cannot remember precise details of past experiences, we may guess that imagined experiences had actually happened, based on a false sense of familiarity that the event had happened, inducing an externalisation bias (Bayen et al., 2000; Küppers & Bayen, 2014). Predictions about how a schema may induce an externalisation bias concerns two kinds of mnemonic advantages: ‘congruency advantage’, a phenomenon where qualities of experiences that are congruent with a schema are often remembered better than unrelated qualities; and ‘incongruency advantage’, where a signal that often reflects a discrepancy between qualities of novel experiences and those reflected in a schema, known as the ‘*prediction error*’, may induce a sense that qualities of new experiences are unfamiliar, enabling reality monitoring decisions based on a sense of familiarity (Greve et al., 2019; Sterzer et al., 2018; Van Kesteren et al., 2012). Congruency advantage, for example, may help us remember both imagined and perceived experiences, facilitating reality monitoring decisions that concern both kinds of experiences. Consistent with this prediction, Experiment 3.2 in chapter 3 observed that participants’ reality monitoring performance tended to increase as participants came across more imagined or perceived experiences with qualities that were congruent with those associated with schemas. Incongruency advantage, in contrast, may facilitate reality monitoring decisions disproportionately: a stronger schema that reflects qualities of perceived experience, for example, may induce a stronger prediction error, which may help us to feel that perceived experiences feel familiar, facilitating reality monitoring decisions concerning perceived experiences, relative to those concerning imagined experiences. Consistent with this prediction, Experiment 3.2 in Chapter 3 observed that participants’ reality monitoring performance concerning perceived experience tended to improve faster, relative to those concerning imagined experiences, ultimately resulting in an externalisation bias. These findings collectively suggest that, even if we have forgotten details of past experiences, our knowledge about common qualities of these experiences may influence subsequent reality monitoring decisions, where a false sense of familiarity may induce misattributions of imagined experiences as those perceived from the outside word.

Across chapters 2 and 3, the reported experiments observed reality monitoring decisions to be associated with memory precision and a false sense of familiarity, respectively, suggesting that reality monitoring performance may be influenced by at least two different kinds of mnemonic processes: recollection, which may involve at least some extent of precision with which details of previous experiences are retrieved and, upon unsuccessful recollection, a response bias, where participants may falsely believe that they had perceived an event even when, in fact, the experience was only imagined.

More broadly, people with generally lower memory precision, on average, may be more susceptible to a false sense of familiarity that an event had happened and, therefore, they may tend to misattribute imagined experiences as perceptions of the outside world. A group of people that exhibit such externalisation biases, for example, include patients with schizophrenia, who often exhibit psychosis symptoms such as hallucinations (Simons et al., 2017). Previous research on psychosis in healthy people, interestingly, observed that people who have no clinical diagnosis nevertheless report traits associated with psychosis, such as schizotypy and proneness to hallucinations (Van Os et al., 2009). Based on these observations, a theoretical account of psychosis known as the 'psychosis continuum model' suggests that cognitive profiles associated with psychosis may vary on a continuum from clinical to healthy people, so some healthy people may indeed exhibit traits associated with psychosis (Meehl, 1962). According to this view from the psychosis continuum model, healthy people with generally lower memory precision may exhibit greater traits of psychosis, including schizotypy (Mason et al., 2005) and proneness to hallucinations (Waters et al., 2003). Inconsistent with this view, however, Experiment 4.1 in chapter 4 did not observe a significant association between memory precision and either schizotypy or proneness to hallucination despite the use of a large sample (N = 160; 82 samples were needed to detect a medium-sized effect with 80% likelihood of detecting such effect). This experiment, however, also did not observe significant individual differences in participants' psychosis traits, suggesting that lack of heterogeneity in the sample may have obscured a possible association with memory precision and psychosis traits. Previous studies that have used similar measures of psychosis traits may have observed similarly low variance in psychosis traits among healthy people, which may explain the mixed evidence for a possible association between qualities of mnemonic representations and psychosis traits (Alderson-Day et al., 2019; Allen et al., 2006, 2006; Collignon et al., 2005; Garrison, Moseley, et al., 2017; Larøi et al., 2004). As such, evidence remained limited for the notion from the psychosis continuum model that healthy people may exhibit cognitive profiles associated with clinical psychosis, including hallucination-like mnemonic representations, which may underlie reduced reality monitoring performance.

To capture enough variance in psychosis traits, Experiment 4.2 replaced traditional measures of psychosis traits with two novel measures based on larger samples: schizotypal personality (Davidson et al., 2016) and anomalous perceptions (Bell et al., 2006). This experiment did observe notable individual differences in participants' schizotypal personality, enabling the exploration of possible associations between qualities of mnemonic representations underlying reality monitoring decisions and schizotypal personality; whereas participants' tendency to experience anomalous perceptions was skewed towards the lower end of the scale, suggesting a possible floor effect. This experiment observed, intriguingly, a positive association (albeit one that did not survive correction for multiple comparisons), where greater precision with which participants remembered details of events correlated with greater schizotypal personality. A possible explanation for this positive association is that people with greater schizotypal traits may first generate vivid episodic simulations and, in turn, remember precise details of these simulations, so that they may anticipate future events. This explanation provides a novel insight, that richer and more vivid mnemonic qualities, which may underlie more accurate reality monitoring decisions, may be associated with greater traits of psychosis.

This positive association observed between memory precision and psychosis traits contrasts with the negative association predicted by the psychosis continuum model, where lower memory precision may first reduce reality monitoring performance and, in turn, lead to greater traits of psychosis (Meehl, 1962). Lower memory precision may indeed be associated with reduced reality monitoring performance, as discussed throughout this thesis, and reduced reality monitoring performance has been often observed in people with clinical psychosis (Simons et al., 2017). These positive and negative associations between qualities of mnemonic representations, reality monitoring decisions, and psychosis traits collectively substantiate the overall argument of the current thesis, that we may keep track of reality in multiple ways.

If there are indeed multiple ways to keep track of reality, there may be at least two directions of relationships between reality monitoring decisions and mnemonic qualities. In one direction of the relationship, mnemonic qualities may influence reality monitoring decisions, as discussed throughout the thesis; whereas in the other direction, for example, the rememberer may decide the original source of the memory even before retrieval, and this pre-retrieval decision may then influence the rememberer to retrieve features of experiences which tend to resemble characteristics often associated with the pre-decided source. Note with caution, however, this pre-retrieval decisions may reflect random anticipatory guesses, rather than post-retrieval reality monitoring decisions which may first involve retrieval of a past experience and then careful assessment of the remembered features and, often resulting in relatively more accurate source monitoring decisions (Johnson et al., 1994).

It may be possible to investigate the possible second direction of influence, where pre-retrieval decision may influence qualities of subsequently remembered experiences, by first reducing reality monitoring performance. Reality monitoring performance may be reduced by applying brain stimulation to a region often associated with reality monitoring performance, medial prefrontal cortex (Brandt et al., 2014; Kensinger & Schacter, 2006; Lagioia et al., 2011; Simons et al., 2006, 2008; Subramaniam et al., 2012; Turner et al., 2008; Vinogradov et al., 2008; Vinogradov et al., 2006). Notably, however, a previous study that applied brain stimulation at medial prefrontal cortex observed one of their participants to report pain during the stimulation, demonstrating an ethical limitation where both this study and possible future studies involving their brain stimulation protocols or alike may induce their participants to experience pain (Subramaniam et al., 2020). Another limitation of this study concerns a small sample size (i.e., 9 participants included in the analysis), which may not be statistically powerful enough to reveal reliable findings. Therefore, the possible causal relationship where pre-retrieval decisions may influence mnemonic qualities remains elusive.

Multivariate Reality Monitoring

Previous theoretical accounts, such as the Source Monitoring Framework and the psychosis continuum model, have been limited in describing multiple relationships between qualities of mnemonic representations, reality monitoring decisions, and psychosis traits. The Source Monitoring Framework, for example, provides an overarching notion that reality monitoring decisions might be affected by the underlying mnemonic qualities (Johnson et al., 1993), but this notion is not specific enough to describe which mnemonic qualities might be involved in reality monitoring decisions, or whether each quality might either enhance or reduce reality monitoring performance. This lack of specific hypotheses have posed a challenge in testing whether mnemonic qualities are indeed associated with reality monitoring decisions. To additionally provide testable hypotheses, the current thesis proposes a relatively more specific theoretical model based on findings from both current and previous research, thereby contributing to the literature on multiple relationships between mnemonic qualities and reality monitoring decisions. This model, which I will refer to as the '*multivariate reality monitoring account*', suggests two main hypothesis: reality monitoring decisions might typically depend on mnemonic quality, such as a sense of self-agency and perceptual details; and that this dependency might be flexible, such that its strength might vary in different situations and between people.

In line with the first hypothesis, experiments reported in Chapter 2 have observed that reality monitoring performance tended to correlate with memory precision, but that performance could still be intact, even when its relationship with the underlying mnemonic quality such as autonoetic consciousness was reduced, suggesting that reality monitoring decisions do not necessarily depend on mnemonic quality. Prior to these experiments, the Source Monitoring Framework only suggested that reality monitoring decisions might depend on multiple mnemonic qualities (Johnson et al., 1993), rather than whether each of these mnemonic qualities might be necessary for reality monitoring decisions. So these findings from the present experiments help to describe how reality monitoring decisions might not necessarily depend on some mnemonic qualities.

Such descriptions are further provided by the multivariate reality monitoring account. According to this account, we may first attempt to recollect details of past experiences, resulting in a mnemonic representation. If this representation is precise, reality monitoring decisions may then depend on the precise qualities of this mnemonic representation. This dependency, however, is not necessary to keep track of reality. If, for example, the precision of recollection is reduced, reality monitoring decisions may instead depend on a sense of whether mental representation feel familiar (see Figure 5.1 for an illustration of the account). Given these flexible, rather than rigid causal, relationships between reality monitoring decisions and multiple mnemonic qualities, it might be possible to postulate that other mnemonic qualities, such as richness of either auditory and visual details, might be flexibly associated with reality monitoring decisions as well. People who tend to experience auditory hallucinations, for example, may exhibit seemingly intact reality monitoring performance concerning visual information, if visual reality monitoring decisions depend on qualities of visual, rather than auditory mental representations. The opposite might be apparent among people who tend to experience visual hallucinations, suggesting that reality monitoring decisions might depend on specific sensory qualities of mnemonic representations, rather than generic mnemonic qualities as described by broad research frameworks such as the Source Monitoring Framework.

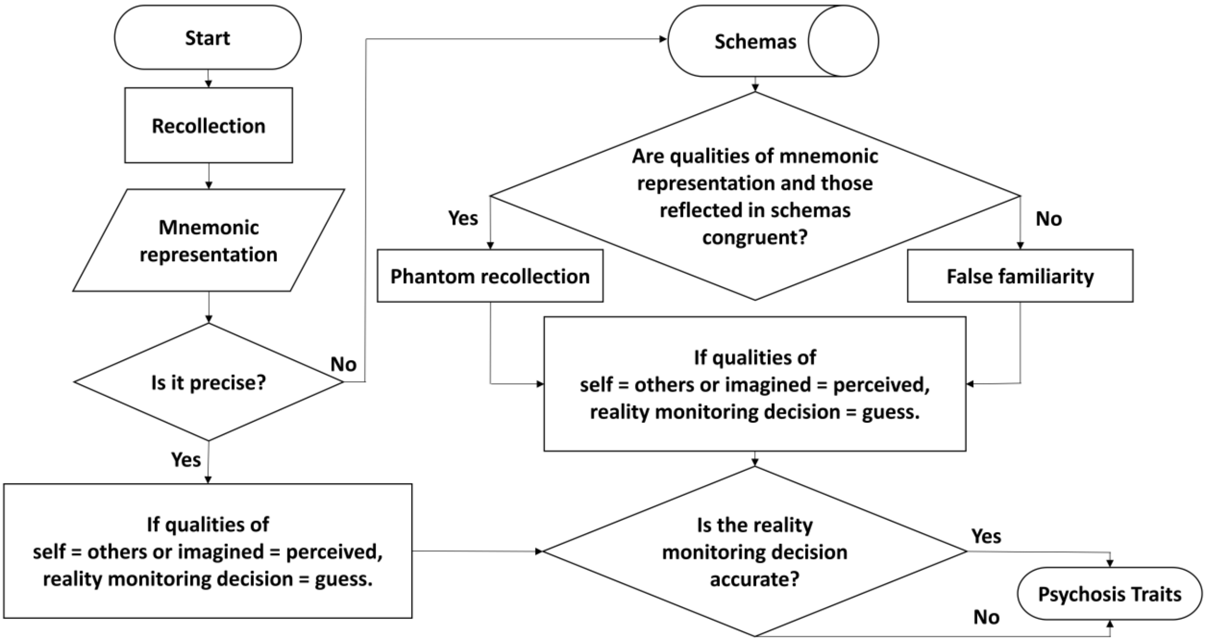

Figure 5.1. A Flowchart Illustration of The Multivariate Reality Monitoring Account. If qualities of self-generated information resemble those of other people, or qualities of imagined and perceived experiences resemble each other, we might confuse these qualities, losing track of reality. The direction of arrows indicate the order of processes, squares represent processes, parallelograms represent either an input or an output, a cylinder represents access to stored information, and diamonds represent decisions.

To test such specific relationships, researchers could measure the qualities of both visual and auditory qualities of mnemonic representations that might underlie reality monitoring decisions. Researchers may, for example, use the experimental paradigms reported in the current thesis to measure visuoperceptual mnemonic qualities. To measure auditory qualities, researchers could first generate speech of word pairs such as ‘Romeo and Juliet’, using software that can manipulate qualities of speech such as the extent of maleness and femaleness of voices on a continuous scale known as ‘Praat’ (Boersma & Van Heuven, 2001). Researchers can then, in the study phase, ask participants to either listen to the speech of both words of a word pair, or hear the first word and imagine the second word. In the later test phase, participants can be presented with the studied word pairs and be asked to both recreate the auditory qualities and indicate whether the second word of the word pair was heard or imagined. By combining these experimental paradigms, researchers can investigate whether people with atypical visual mnemonic qualities may exhibit lower reality monitoring performance concerning visual, relative to auditory, information, and the other way around for people with atypical auditory mnemonic qualities. Combining these experimental paradigms stemming from the multivariate reality monitoring account might help to reveal dissociations between different kinds of relationships between mnemonic qualities and reality monitoring decisions.

Turning to the psychosis continuum model, it suggests that cognitive profiles associated with clinical psychosis, such as reduced reality monitoring performance, might be observable among healthy people. As discussed in Chapter 4 of the current thesis, however, reduced reality monitoring performance is not necessarily associated with traits of psychosis, suggesting that the psychosis continuum model might be limited in describing how people with different mnemonic qualities might keep track of reality. In contrast, the multivariate reality monitoring account might help to describe different ways in which such groups of people keep track of reality. Previous studies involving amnesiac patients with damage in brain regions that have been associated with post-retrieval monitoring abilities such as the frontal lobe, for example, have observed that patients tend to exhibit reduced reality monitoring performance, relative to healthy controls, suggesting that amnesiacs may lose touch with reality because their post-retrieval monitoring abilities are reduced, rather than just the quality of mnemonic representations (Baddeley & Wilson, 1988; Johnson, 1988). In contrast, people whose ability to generate vivid mental representations, such as aphantasiacs, might struggle to keep track of reality because the quality of their mnemonic representations tends to be lower than average, rather than their post-retrieval monitoring abilities (Dawes et al., 2020). On the other end of the scale of people with different mnemonic qualities, people who tend to experience extremely vivid memories of disturbing events or ‘flashbacks’ might misattribute exaggerated qualities as real (Golier et al., 1997; McNally et al., 2005). Moreover, people with vivid memories of imagined experiences, such as both clinical and non-clinical voice-hearers, might exhibit distinguishable reality monitoring performance: clinical voice-hearers might exhibit reduced reality monitoring performance when one of their mnemonic qualities was reduced, possibly because they were less able to consider different multiple mnemonic qualities to make reality monitoring decisions; whereas non-clinical voice-hearers might exhibit intact reality monitoring performance, because they managed to consider multiple mnemonic qualities in reality monitoring decision making, enabling them to keep track of reality even if some of their mnemonic qualities tend to be atypical, resembling vivid hallucinations. Taken together, the multivariate reality monitoring account may help to understand specific ways in which people keep track of reality, relative to more broad theoretical accounts such as the psychosis continuum model.

These specific ways of keeping track of reality, however, may be challenging to investigate. Patients with amnesia and selective frontal lobe damage, for example, are relatively rare and, therefore, the statistical power with which researchers could investigate patients' reality monitoring abilities may be limited. Alternatively, researchers could temporarily simulate cognitive profiles of patients, by stimulating the frontal lobe among healthy people, although a substantially more disruptive brain stimulation protocol than those used in Experiments 2.3 and 2.4 may need to be applied, to ensure that reality monitoring performance is reduced. This potentially more disruptive approach may, however, pose a risk to the well-being of the participants (Rossi et al., 2009).

A relatively safer approach involves a computational model that comprise of two separate components: the 'generator', which aims to generate information with qualities that resemble those from the real outside world; and the 'moderator', which aims to distinguish information generated by the generator from those generated from the outside world (Gershman, 2019). Researchers can, for example, use generators to produce visual images and, in turn, test whether the moderator can distinguish these images from images of the outside world. If qualities of images generated by the generator and those of the outside world tend to be distinguishable from each other, the moderator may be able to distinguish these qualities, keeping track of the original sources of images. When the moderator is disrupted by reducing its activity, however, the moderator may become less able to keep track of the original sources of images even if the qualities of images tend to be good, possibly resembling how amnesiacs with a frontal lobe damage struggle to keep track of internal and external sources of information.

Similarly, such a computational model might help to reveal how people with traumatic experiences keep track of reality. People who have experienced speech with negative emotional qualities or verbal abuse, for example, might both remember precise details of these experiences and imagine similar experiences, so that they may anticipate and avoid such experiences in the future. Emotional qualities of both their perceived and imagined experiences may come to be negative on average, resembling each other and, ultimately, reducing reality monitoring performance concerning auditory verbal information. To still keep track of reality, these people may turn to assess whether visual qualities of perceived and imagined experiences that tend to be distinguishable from each other, adapting to consider relatively more distinguishable mnemonic qualities to make reality monitoring decisions. Investigating this possible adaptation, however, might involve presenting negatively-valenced stimuli such as verbal abuse to participants, raising ethical questions about whether such investigation should involve human participants. Alternatively, a generator-moderator model can be used to first generate auditory and visual information and, in turn, test whether adding negative emotional qualities to auditory information generated by both the generator and from the outside world might induce the moderator to adapt, such that the moderator may come to decide the original sources of information by distinguishing visual qualities of information, rather than those concerning auditory qualities.

Taken together, theoretical accounts that could describe specific relationships observed between reality monitoring decisions and mnemonic qualities, including the multivariate reality monitoring account and the generator-moderator model, might help to describe specific ways in which reality monitoring decisions might depend on multiple mnemonic qualities. These descriptions may help to fill in some of the gaps in the general notion from the Source Monitoring Framework, that reality monitoring decisions depend on mnemonic qualities, and a notion from the psychosis continuum model, that cognitive profiles associated with clinical psychosis may be observed among healthy people.

Limitations and Future Directions

The current thesis has, thus far, argued that multiple relationships may exist between reality monitoring decisions and mnemonic qualities. Whether these relationships may be necessary for keeping track of reality, however, remains unresolved. One of the approaches that can test the necessity of these relationships is to investigate causal neurocognitive bases of these relationships, by first disrupting activity in a brain region that has been associated with a cognitive function of interest and, in turn, observing whether the disruption disrupts performance of that cognitive function. Brain stimulation experiments in Chapter 2 sought to test such causal neurocognitive relationships, by disrupting activity of angular gyrus that tracks memory precision, to observe whether the disruption reduces memory precision. If, for example, reality monitoring decisions depend on mnemonic qualities such as the precision of recollection, then reducing memory precision would be predicted to reduce reality monitoring performance, revealing a neurocognitive basis of the relationship between reality monitoring decisions and the underlying mnemonic qualities. These brain stimulation experiments did not, however, observe the stimulation of angular gyrus to significantly reduce memory precision, limiting the inferences that can be drawn from these experiments about the causal neurocognitive basis of memory precision and its relationship with reality monitoring decisions.

These brains stimulation experiments may not have observed the stimulation of angular gyrus to significantly reduce memory precision possibly because brain stimulation may not have disrupted activity in the angular gyrus region of interest in every participant. Effects of brain stimulation, for example, may be reduced as distance increases between the centre of the coil, from which brain stimulation is applied, and the target brain region (Walsh & Pascual-Leone, 2003). If some participants' angular gyrus tended to be further away from the position of the coil, the effect of stimulation may have been reduced or absent among these participants, resulting in apparently intact memory precision. While it is possible to estimate the distance between the position of the coil and the location of angular gyrus, only half of the participants in Experiments 2.3 and 2.4 were registered to their structural brain scan, so these experiments might not have had enough statistical power to explore a possible associations between the distance and the magnitude of the effect of stimulation. Moreover, it is possible that applying stimulation at angular gyrus disrupted the activity in angular gyrus, but Experiment 2.3 did not measure activity in angular gyrus during task performance, so I can only postulate, but not empirically test, whether the reduction in autonoetic consciousness observed in Experiment 2.3 was caused by reduced activity in angular gyrus.

To test whether brain stimulation of angular gyrus disrupted activity in angular gyrus, relative to control stimulation, neural activity could be measured while participants are making reality monitoring decisions. A possible method that can measure neural activity in real time may include concurrent brain stimulation and neuroimaging. A future study, for example, could investigate whether stimulation of angular gyrus, relative to control stimulation, reduces haemodynamic activity in angular gyrus during the period when reality monitoring decisions are being made. Such tests may help us to understand neurocognitive processes that may be vital for making reality monitoring decisions, which might depend on the precision with which we remember past experiences.

Turning to findings discussed in Chapter 3, a possible neurocognitive basis remains elusive for the false sense of familiarity that imagined experiences had actually happened. Chapter 3 discussed that, when we forget details of past experiences, reality monitoring decisions may depend on a sense of familiarity, rather than precise recollection. So it seems possible that, when the precision of recollection tend to be greater, neural activity that correlates with reality monitoring decisions and recollection might become more closely associated with each other; If, however, we forget precise details of past events, the neural correlates of reality monitoring decisions might be associated with those of familiarity, rather than recollection. According to this view, distinct neurocognitive relationships may exist between reality monitoring decisions and two distinct retrieval processes: familiarity and recollection. Future studies may investigate these distinct neurocognitive relationships, for example, by first measuring electrophysiological activity patterns that track with familiarity and recollection (see Rugg & Curran (2007) for examples). Future studies may then investigate a possible interaction, where neural activity that tracks with reality monitoring decisions and familiarity may become more closely linked, particularly when memory precision diminishes after a long time (e.g., 24 hours); whereas similar neurocognitive links between reality monitoring decisions and recollection may decrease. This future investigation may help us to understand currently elusive neurocognitive bases of relationships between reality monitoring decisions and different mnemonic qualities.

A broader limitation concerns methods we might use to investigate qualities of mental experiences. Experiments reported in the current thesis, for example, presented a black cross, which involves less perceptual details than an actual image of an object, when participants were asked to imagine objects moving progressively to a location; whereas actual images of objects were presented when participants were asked to perceive objects progressively moving to a location, which may have enriched visuoperceptual qualities of perceived experiences, relative to imagined experiences. These different visual cues (i.e., black cross and actual images) may have exaggerated qualitative differences between imagined and perceived experiences, confounding the qualities of these experiences. To reduce the likelihood of the qualities of visual cues from confounding the qualities of remembered experiences, future studies may benefit from matching the visual qualities of these cues. Note with caution, however, previous research has, for example, observed that people often report less perceptual details when they are asked to report qualities of imagined experiences, relative to perceived experience, suggesting that imagined experiences may typically involve less perceptual details than perceived experiences (Johnson, 1988). So artificially matching qualities of visual cues may obscure typically different qualities of imagined and perceived experiences and, in turn, obscure how these qualities may be associated with reality monitoring decisions. Therefore, future studies may benefit from investigating how visual qualities of cues may affect qualitative differences between imagined and perceived experiences.

Another method often used to investigate qualities of mental experiences is self-report scales, but these scales may not be sufficient to capture a wide variance in, for example, proneness to hallucinations or anomalous perceptions. In line with this view, experiments reported in chapter 4 observed that participants' scores on both measures of proneness to hallucinations and anomalous perceptions tended to be on the lower end of the scale, limiting these experiments' ability to investigate how qualities of mental experiences may be related to cognitive profiles associated with reality monitoring performance. To capture a wider individual difference in qualities of mental experiences, which may be particularly subtle in healthy populations relative to people with clinical psychosis, future studies may benefit from using a more sensitive measure of mental representational quality. One of the measures may include a series of questions related to experiences of hallucinations, to which participants provide short qualitative descriptions of their mental experiences (Stanghellini et al., 2012). Such qualitative measures may be more sensitive at measuring different qualities of hallucinatory experiences, relative to traditional measures of psychosis traits that involve binary yes-or-no responses or Likert scales.

Moving onto remaining questions that concern wider research on reality monitoring, we may not yet understand whether reality monitoring decisions tend to depend on some mnemonic qualities more than other qualities. If, for example, more realistic qualities of imagined experiences, such as rich perceptual details, tend to be more rewarding, we may come to remember more imagined experiences with realistic rather than unrealistic qualities. So reality monitoring decisions may, on average, come to depend on more realistic qualities of imagined experiences, even when such realistic qualities of imagined experiences resemble qualities of perceived experiences, blurring the qualitative differences between these experiences. We may, therefore, misattribute the original sources of these experiences, leading to greater confusion between real and imagined events. This view, that some mnemonic qualities may be more closely associated with reality monitoring decisions, and that these associations may ultimately affect our ability to keep track of reality remains unexplored.

Conclusion

The experiments reported in the current thesis observed multiple relationships between reality monitoring decisions and qualities of mnemonic representations. Chapter 2 observed that we may misattribute our past actions to another person, particularly when the precision with which we remember the respective action tends to be reduced. The neurocognitive basis of this ability to keep track of our past actions may include angular gyrus, which may facilitate a sense of re-living the past, a key element of episodic memory known as autonoetic consciousness (Tulving, 1983). We may also misattribute imagined experiences as perceptions of the outside world, particularly when products of our imaginations tend to involve qualities often expected of perceptions, such as unusually precise visuoperceptual details. This ability to keep track of imagined experiences may involve brain regions other than angular gyrus, such as anterior prefrontal cortex (Simons et al., 2017). Chapter 3 observed how we may keep track of reality when, sometimes, reality monitoring decisions cannot depend on precise recollection, because we may have forgotten precise details of past experiences. In such situations, reality monitoring decisions may instead depend on a false sense of familiarity that an event has happened, inducing a tendency to misattribute imagined experiences as perceptions. Chapter 4 observed how some healthy people with greater traits of psychosis may tend to imagine realistic simulations of future situations and, in turn, remember precise details of these simulations to anticipate such situations. When qualities of these simulations resemble those often expected of perceived experience, we may confuse real and imagined events. Chapter 5 discussed that multiple relationships between reality monitoring decisions and underlying mnemonic qualities may be better explained by a combination of previously separate theoretical accounts: the Source the Source Monitoring Framework (Johnson et al., 1993), the Fuzzy Trace Theory (Brainerd et al., 2008; Brainerd & Reyna, 1998), the guessing hypothesis (Bayen et al., 2000; Küppers & Bayen, 2014), and predictions regarding congruency and incongruency advantages (Greve et al., 2019; Sterzer et al., 2018; Van Kesteren et al., 2012). A single theoretical account, such as the psychosis continuum model (Meehl, 1962), may be insufficient to describe the multiple ways in which we may keep track of reality. Instead, a multivariate model was proposed, providing a combined account that attempts to explain the multiple relationships between mnemonic qualities and reality monitoring decisions.

Overall, findings reported in the current thesis are consistent with a prominent theoretical view, that our ability to keep track of reality may depend on the quality of underlying mnemonic representations, including the precision with which we remember personal past experiences or episodic memory precision. These findings provide novel insights that multiple relationships may exist between reality monitoring decisions and underlying mnemonic qualities. Reality monitoring decisions may typically depend on qualities associated with episodic memory, but when we cannot remember details of past experiences, they may instead depend on qualities associated with general semantic characteristics or gist memory, such as whether a stimulus evokes a sense of familiarity. A multivariate model that combines elements of previous theoretical accounts, each providing different levels of explanation, seems to better describe these multiple relationships reported in the current thesis, rather than just one level of explanation from any one of the accounts on their own. Limitations of current experiments, such as those concerning causal neurocognitive relationships and how we may estimate qualities of mental experiences, have been discussed. Future studies may improve upon these limitations to further investigate how reality monitoring decisions may interact with multiple mnemonic qualities.

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Appendix

Appendix A: Psychosis Traits Self-Report Scales

Brief Oxford-Liverpool Inventory of Feelings and Experiences

1. Do you enjoy many different kinds of play and recreation? *(Negative Item)*

2. Do your thoughts sometimes seem real as actual events in your life?

3. Has dancing or the idea of it always seemed dull to you?

4. Does it often happen that nearly every thought immediately and automatically suggests an enormous number of ideas?

5. Is trying new foods something you have always enjoyed? *(Negative Item)*

6. Do you sometimes feel that your accidents are caused by mysterious forces?

7. Are there very few things that you have ever really enjoyed doing?

8. Does your voice ever seem distant or far away?

9. Are you much too independent to really get involved with other people?

10. Have you sometimes had the feeling of gaining or losing energy when certain people look at you or touch you?

11. Do you think having close friends is not as important as some people say?

12. Does a passing thought ever seem so real it frightens you?

13. Are you rather lively? *(Negative Item)*

14. When you look into the mirror does your face sometimes seem quite different from usual?

15. Are people usually better off if they stay aloof from emotional involvements with people?

16. Have you ever felt that you have special, almost magical powers?

17. Can just being with friends make you feel really good? *(Negative Item)*

18. On occasions, have you seen a person’s face in front of you when no one was in fact there?

19. When things are bothering you, do you like to talk to other people about it? *(Negative Item)*

20. Is your hearing sometimes so sensitive that ordinary sounds become uncomfortable?

21. Have you had very little fun from physical activities like walking, swimming or sports?

22. Do ideas and insights sometimes come to you so fast that you cannot express them all?

23. Is it fun to sing with other people? *(Negative Item)*

24. Have you felt as though your head or limbs were not your own?

25. Do people who try to get to know you better usually give up after a while?

26. Have you ever thought you heard people talking only to discover that it was in fact some nondescript noise?

27. Do you usually have very little desire to buy new kinds of food?

28. Have you sometimes sensed an evil presence around you, even though you could not see it?

29. Do you like going out a lot?

30. Are your thoughts sometimes so strong that you can almost hear them?

Modified Launay-Slade Hallucinations Scale Revised

1. Sometimes a passing thought will seem so real that it frightens me

2. Sometimes my thoughts seem as real as actual events in my life

3. No matter how much I try to concentrate on my work, unrelated thoughts always creep into my mind

4. In the past I have had the experience of hearing a person’s voice and then found that there was no-one there

5. The sounds I hear in my daydreams are generally clear and distinct

6. The people in my daydreams seem so true to life that I sometimes think they are

7. In my daydreams I can hear the sound of a tune almost as clearly as if I were actually listening to it

8. I often hear a voice speaking my thoughts aloud

9. I have been troubled by hearing voices in my head

10. On occasions I have seen a person’s face in front of me when no-one was in fact there

11. I have heard the voice of the Devil

12. In the past I have heard the voice of God speaking to me

13. When I look at things they appear strange to me

14. I see shadows and shapes when there is nothing there

15. When I look at things, they look unreal to me

16. When I look at myself in the mirror I look different

Schizotypy Personality Questionnaire (Brief Revised Updated)

1. I sometimes feel that people are talking about me.
2. I sometimes feel that other people are watching me.
3. When shopping, I get the feeling that other people are taking notice of me.
4. I often feel that others have it in for me.
5. I sometimes get concerned that friends or co-workers are not really loyal or trustworthy.
6. I often have to keep an eye out to stop people from taking advantage of me.
7. I feel that I cannot get 'close'• to people.
8. I find it hard to be emotionally close to other people.
9. I feel that there is no one I am really close to outside of my immediate family, or people I can confide in or talk to about personal problems.
10. I tend to keep my feelings to myself.
11. I rarely laugh and smile.
12. I am not good at expressing my true feelings by the way I talk and look.
13. Other people see me as slightly eccentric (odd).
14. I am an odd, unusual person
15. I have some eccentric (odd) habits.
16. People sometimes comment on my unusual mannerisms and habits.
17. I often feel nervous when I am in a group of unfamiliar people.
18. I get anxious when meeting people for the first time.
19. I feel very uncomfortable in social situations involving unfamiliar people.

20. I sometimes avoid going to places where there will be many people because I will get anxious.
21. I believe in telepathy (mind-reading).
22. I believe in clairvoyance (psychic forces, fortune telling).
23. I have had experiences with astrology, seeing the future, UFO's, ESP, or a sixth sense.
24. I have felt that I was communicating with another person telepathically (by mind-reading).
25. I sometimes jump quickly from one topic to another when speaking.
26. I tend to wander off the topic when having a conversation.
27. I often ramble on too much when speaking.
28. I sometimes forget what I am trying to say.
29. I often hear a voice speaking my thoughts aloud.
30. When I look at a person or at myself in a mirror, I have seen the face change right before my eyes.
31. My thoughts are sometimes so strong that I can almost hear them.
32. Everyday things seem unusually large or small.

Cardiff Anomalous Perceptions Scale

1. Do you ever notice that sounds are much louder than they normally would be?

2. Do you ever sense the presence of another being, despite being unable to see any evidence?

3. Do you ever hear your own thoughts repeated or echoed?

4. Do you ever see shapes, lights or colours even though there is nothing really there?

5. Do you ever experience unusual burning sensations or other strange feelings in or on your body?

6. Do you ever hear noises or sounds when there is nothing about to explain them?

7. Do you ever hear your own thoughts spoken aloud in your head, so that someone near might be able to hear them?

8. Do you ever detect smells which don’t seem to come from your surroundings?

9. Do you ever have the sensation that your body, or a part of it, is changing or has changed shape?

10. Do you ever have the sensation that your limbs might not be your own or might not be properly connected to your body?

11. Do you ever hear voices commenting on what you are thinking or doing?

12. Do you ever feel that someone is touching you, but when you look nobody is there?

13. Do you ever hear voices saying words or sentences when there is no-one around that might account for it?

14. Do you ever experience unexplained tastes in your mouth?

15. Do you ever find that sensations happen all at once and flood you with information?

16. Do you ever find that sounds are distorted in strange or unusual ways?

17. Do you ever have difficulty distinguishing one sensation from another?

18. Do you ever smell everyday odours and think that they are unusually strong?

19. Do you ever find the appearance of things or people seems to change in a puzzling way, e.g. distorted shapes or sizes or colour?

20. Do you ever find that your skin is more sensitive to touch, heat or cold than usual?

21. Do you ever think that food or drink tastes much stronger than it normally would?

22. Do you ever look in the mirror and think that your face seems different from usual?

23. Do you ever have days where lights or colours seem brighter or more intense than usual?

24. Do you ever have the feeling that of being uplifted, as if driving or rolling over a road while sitting quietly?

25. Do you ever find that common smells sometimes seem unusually different?

26. Do you ever think that everyday things look abnormal to you?

27. Do you ever find that your experience of time changes dramatically?

28. Have you ever heard two or more unexplained voices talking with each other?

29. Do you ever notice smells or odours that people next to you seem unaware of?

30. Do you ever notice that food or drink seems to have an unusual taste?

31. Do you ever see things that other people cannot?

32. Do you ever hear sounds or music that people near you don’t hear?