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The Role of Autonomic Arousal in Curiosity Sparked by Unsuccessful Memory Recall

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Abstract

States of curiosity, which reflect temporary motivational tendencies to seek out information, play a critical role in learning and memory. Recent work from our lab suggests that metacognitive retrieval experiences related to unsuccessful memory recall can spark curiosity; we have found that feeling-of-knowing (FOK) experiences predict to what extent participants will subsequently seek information they cannot recall. Here, we asked whether autonomic arousal plays a role in the generation of this retrieval-induced curiosity. Further, we asked if subsequent access to the information that cannot be recalled is rewarding and whether autonomic arousal plays a role in the anticipation of reward. We examined pupil size as a marker of autonomic arousal while participants made FOK judgments about previously studied face-name pairs they could not recall. Subsequently, participants were provided limited opportunities to seek out names and asked to rate their level of satisfaction upon viewing selected names. Behaviourally, we replicated our previous findings, with FOK experiences predicting information seeking and found that access to unrecalled information was rewarding as indicated by satisfaction ratings. Our pupillary results showed that as retrieval-induced curiosity increased, so did autonomic arousal, but arousal levels were not linked to subsequent information seeking though were found to play a role in the anticipation of the relief of curiosity. These results suggest that autonomic arousal plays a role in the induction of curiosity, but the motivation to seek missing information may not be driven by autonomic arousal, and furthermore that anticipatory autonomic arousal may reflect anticipation of rewarding information.

Keywords

Curiosity; autonomic arousal; memory retrieval; pupil response; metacognition.

Summary for Lay Audience

Curiosity is a pervasive experience that we intuitively understand and associate with learning. Yet, little is understood about how curiosity drives learning. One common curiosity experience involves seeing someone that is recognizable, for instance, at the grocery store, and having a sense that we know them and know their name but cannot bring the name to mind. Interestingly, we often feel we know their name and could even recognize it if presented to us. We often feel frustrated and motivated to find the name and will feel satisfied if we do. Scientists call this a feeling-of-knowing (FOK), which is a sense of knowing information without being able to remember it while feeling like the information would be recognized if seen. Researchers have shown FOK inspires curiosity, essentially motivating people to seek out the missing information. The frustration that is often felt when information cannot be recalled in this type of experience suggests that a state of arousal could be involved. Arousal is the mobilization of energy by a part of the nervous system involved in survival responses. Arousal is also involved in increasing the level of overall stimulation to ready us for a response. Additionally, the satisfaction that is felt when we obtain the missing information in a FOK experience suggests the information may be playing the role of a reward, similar to how food satisfies hunger. This study explored the role of arousal and reward anticipation in curiosity that was induced by FOK experiences. FOK experiences were induced by presenting faces with names, for which the names subsequently could not be recalled. We used pupil dilation response as a measure of arousal. We found arousal was present in curiosity inspired by unsuccessful recall in FOK experiences but that this arousal did not appear to motivate seeking out the missing information. We showed that obtaining missing information was more rewarding when people were more curious about it and that arousal was present when they anticipated obtaining missing information. These results suggest that a desire to obtain the rewarding information is what motivates people to seek out the missing information.

Co-Authorship Statement

Dr. Stefan Kohler guided the research project as my supervisor. He provided guidance on project development and design, relevant literature, data analyses, and interpretation of the results.

Two Ph.D. candidates in Dr. Stefan Kohler's lab, Gregory Brooks and Haopei Yang, assisted me with various aspects of this research project. Gregory supported me with project design, analysis of the behavioural results, and interpretation of the results. Haopei assisted me in the experimental setup, the analysis of the pupillary data, and the interpretation of the results.

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Introduction

1 Introduction

1.1 Overview

Imagine the following scenario: Upon viewing the image of a person on a social media site, you have an immediate sense of recognition but are unable to recall their name. You have a strong sense you know their name and that you would be able to recognize it if it were shown to you. You recollect specific facts about this person, such as remembering they are a prominent memory researcher who won a Nobel Prize in economics. However, despite your best efforts, you just cannot bring this person's name to mind. You feel an urgent need to remember the name and a growing sense of frustration. You are motivated to seek out the missing information, and so you do what many would do in this situation - you Google it. You Google the various facts you recall about the person until you finally resolve this sense of urgency by discovering the name you felt you knew all along – Daniel Kahneman. Upon seeing the name, you feel a sense of immediate recognition and relief and satisfaction.

The presented scenario illustrates an experience familiar to most people. Psychologists call this metacognitive phenomenon a feeling-of-knowing experience. It is a sense of knowing a piece of information without actually being able to recall it while simultaneously sensing the information would be recognized if presented (Hertzog et al., 2010; Koriat, 2000; Souchay et al., 2002). In the described fictive scenario, the feeling-of-knowing experience seemed to influence behaviour, leading to subsequent information seeking via an internet search to find the name that could not be recalled. Broadly, curiosity is defined as information seeking (Kidd & Hayden, 2015). Therefore, in the presented scenario, it is as if the inability to remember the name induced a state of curiosity, an idea supported by research recently conducted by Brooks et al. (2021). While the scenario presented is imaginary, it illustrates an experience common to most people. The scenario highlights how not being able to remember a name during a feeling-of-knowing experience can induce curiosity and also points to some potential physiological aspects of the experience. The sense of urgency and frustration that arose when not being able to recall the information--in this case, the name--suggests a potential role for autonomic arousal in this type of curiosity experience. Additionally, the sense of relief and satisfaction experienced when the information was uncovered suggests that searching for and finding the missing piece of information may be a rewarding experience.

It is with this scenario in mind that my research question was developed. In this thesis, I will examine the role of autonomic arousal and reward anticipation in curiosity induced by unsuccessful memory recall. I will use the pupillary response as a marker of arousal while inducing curiosity based on unsuccessful memory recall in an experimental feeling-of-knowing paradigm that mimics key aspects of the scenario presented here.

1.2 Curiosity

1.2.1 What is curiosity?

In order to examine the role of autonomic arousal and reward anticipation in curiosity, it is important to understand its scientific definition. In my example and examined in this research, the type of curiosity referred to in my example is epistemic curiosity. Epistemic curiosity is a motivational state to seek out information for no other purpose than to obtain the desired information (Kidd & Hayden, 2015). While commonly epistemic curiosity is described as being intrinsically motivated, it can be difficult to establish with certainty that it is entirely intrinsic, and so for the purposes of my research, I will focus on the information seeking aspect of the definition.

Ultimately, epistemic curiosity drives a person to seek out information to fill an information gap. According to Lowenstein’s (1994) theory of epistemic curiosity, curiosity is stimulated from the feeling of uncertainty that arises when there is an information gap, namely a difference between what one wants to know and what one actually knows. In this case, curiosity is experienced as a ‘wanting’ of information, similar to how hunger is experienced as a desire for food. Akin to hunger motivating an individual to seek out food, curiosity drives an individual to seek out the missing information. Similar to obtaining food when hungry, the desired information will satiate and decrease the level of curiosity and may be experienced as rewarding. Other prominent curiosity researchers have suggested a role for reward, like Lowenstein, but also highlighted the potential for aversiveness in the curiosity experience. In his theory of epistemic curiosity, Berlyne (1954) hypothesized that curiosity is an aversive state that stimulates autonomic arousal and that its termination is both rewarding and of benefit to memory. Thus, prominent theorists in the field suggest a role for autonomic arousal and reward anticipation in the curiosity experience. As noted, in my research, I will examine specifically how this relates to curiosity induced by unsuccessful memory recall.

1.2.2 Curiosity motivates learning and memory

Curiosity is a pervasive experience that plays an important role in learning and memory (Gottlieb et al., 2016). In fact, according to Lowenstein's theory of curiosity (1994), the main function of curiosity is to motivate learning. Similarly, Berlyne (1954) postulated that the relief of curiosity enhances memory. Several studies have shown that declarative long-term memory encoding and consolidation are indeed enhanced by curiosity. Declarative long-term memory, the type of memory examined in this research paper, is what is typically thought of as memory. It reflects the learning and retrieval of personally experienced events, known as episodic memory, and general information or facts, also called semantic memory (Lum & Conti-Ramsden, 2013; Poettrich, 2009; Squire, 1992; Tulving & Markowitsch, 1998).

Previous studies have established a relationship between curiosity and declarative long-term memory. For example, Kang et al. (2009) found that individuals learned the answers to trivia questions best when they were most curious about those questions. While participants were in a functional magnetic resonance imaging (fMRI) scanner, Kang et al. showed them a series of trivia questions and asked them to rate their curiosity for each item. Before being shown the answers, participants were also asked to guess the answers and indicate how confident they felt about their guesses. When participants viewed the answers to trivia questions, brain regions associated with learning and memory (e.g., bilateral putamen, left inferior frontal gyrus, hippocampus) were more activated for items that had been guessed incorrectly than those that had been guessed correctly. Critically, these activations were modulated by the level of curiosity, with activation being greater for questions rated higher in curiosity. Kang et al. conducted a follow-up experiment outside of the scanner, where they administered participants the same task and tested them on their memory of the answers to the trivia questions 11 and 16 days later. After these delays, they found that participants remembered the answers better for items that had initially been guessed incorrectly and had been rated higher in curiosity than those items that had been guessed correctly or rated lower in curiosity. In this paradigm, information could only be new when the guesses were incorrect, given that the information would have been known to the participants if they guessed an answer correctly. Kang et al., therefore, concluded that their results provide evidence that curiosity enhances memory consolidation and that curiosity enhances memory specifically for new information.

Similarly, Brod and Breitwieser (2019) showed that memory for answers to numerical fact-based trivia questions was better for items rated higher in curiosity. They tested whether the learning improvement observed when making predictions on answers to questions (Brod et al., 2018) is mediated by curiosity. They did so by examining curiosity ratings and learning outcomes for trivia questions when participants made predictions about the answers compared to when they only provided examples before viewing the answers. In this way, they could test if the curiosity induced by generating predictions improved learning outcomes, rather than another factor such as retrieving prior knowledge. Brod and Breitwieser found that curiosity ratings were higher for questions when predictions were made compared to when only examples were given and that the answers to questions rated higher in curiosity were better remembered than lower-rated items. They concluded that curiosity promotes learning. Brod and Breitwieser theorized that curiosity might enhance learning by increasing the noradrenergic or autonomic arousal response. They developed this theory based on the behavioural data from this experiment, together with pupillary data they collected while participants undertook the memory task. The pupillary results of their experiment will be discussed further in a subsequent section.

Other researchers have shown that not only does curiosity enhance learning for information attended to directly, but it also enhances memory for incidentally presented information (Galli et al., 2018; Gruber et al., 2014; Stare et al., 2018). Gruber et al. (2014) showed that memory for the answers to trivia questions was enhanced when individuals were more curious about the questions for testing within about 1 hour of encoding and when testing was delayed by one day. Critically, they found that memory for unrelated faces shown when encoding the answers to questions was also improved when participants were more curious about the questions, showing that curiosity enhances memory even for incidental stimuli.

Researchers Marvin and Shohamy (2016) demonstrated the memory-enhancing effect of curiosity in a different paradigm, specifically a willingness-to-wait paradigm. Willingness to wait is a common proxy for the value of information, with individuals waiting longer for high-value information. If curiosity increases the value of information, it should also increase the willingness to wait. Marvin and Shohamy tested participants on their willingness to wait for the answers to a set of trivia questions that they also rated in curiosity, then tested their later recall of the answers. Unlike the other studies, the researchers also asked participants to rate satisfaction upon viewing the answers. Marvin & Shohamy found that participants were more willing to wait for items they felt more curious about and that they were better at remembering the answers to questions they had rated higher in curiosity. These results showed that curiosity increases the value of information and hence potential reward. Further, examining satisfaction scores and how they relate to curiosity ratings led Marvin & Shohamy to conclude that the information prediction error related to the perceived and actual reward value of information enhances learning.

1.2.3 Curiosity involves reward anticipation

Marvin and Shohamy (2016) postulate that information is in itself rewarding and that curiosity is the motivation to obtain that reward, similar to how hunger is the motivation to obtain a food reward. When comparing brain regions activated during looking at pictures of food versus feeling curious when watching magic tricks, researchers Lau et al. (2020) found that the striatum, a reward region of the brain, was activated during both experiences. They also found that brain activation predicted behaviour that would resolve these states. Researchers have shown that people are willing to sustain costs to have curiosity satisfied independent of extrinsic reward (Bennett et al., 2016) and are also willing to take risks to satisfy it (Hsee & Ruan, 2016; Lau et al., 2020). FitzGibbon et al. (2020) postulate that incentive salience may motivate a person to seek out information, specifically the feeling of ‘wanting’ that increases in anticipation of a reward, separate from the pleasurable response of ‘liking’ that is experienced when the sought-after reward is achieved.

Reward anticipation could explain the relationship between curiosity and memory. In their 2016 study, Marvin and Shohamy examined how the information prediction error, namely the difference between the anticipated value of information (i.e., curiosity about the answers to trivia questions) and actual value of information (i.e., satisfaction upon viewing the answers to trivia questions), influenced later memory for trivia answers. They found that memory was best for answers when the gap was largest between the satisfaction rating and curiosity rating, particularly when the satisfaction rating was greater than the curiosity rating. They interpreted these results as showing that the information prediction error enhances learning, ultimately supporting the idea that information can function as a reward, much like food.

Curiosity has been found to involve reward circuitry typically activated in survival-based drives like hunger and thirst (Gruber et al., 2014; Kang et al., 2009). Kang et al. conducted fMRIs on participants while they viewed trivia questions, made predictions about the answers, and provided confidence ratings about their guesses, followed by viewing the answers to the questions. They found that brain regions typically associated with reward were more activated when participants viewed trivia questions they had rated higher in curiosity than those rated lower. These brain regions included the left caudate, bilateral prefrontal cortex, putamen, and globus pallidus.

Activation of brain reward circuitry has also been linked to the curiosity experience and the memory-enhancing effects of curiosity for both related and incidental information. Gruber et al. (2014) had participants rate their curiosity about trivia questions. In an fMRI scanner, they asked them to try to memorize either the associated answers or unrelated face stimuli. About one hour later, they tested participants for recall of trivia answers and recognition of faces. When viewing trivia questions, Gruber et al. found that activation in reward regions of the brain, namely the nucleus accumbens and ventral striatum and the substantia nigra/ventral tegmental area complex (SN/VTA), increased linearly as curiosity ratings increased. Learning outcomes were better for trivia answers and incidental information associated with high curiosity questions. Gruber et al. conducted analyses to understand better how curiosity enhanced learning outcomes related to brain activation. They found that when participants anticipated the answers to trivia questions, activity in the nucleus accumbens and right hippocampus predicted successful recall on a later memory test for questions rated high in curiosity but not for those items rated low in curiosity. Additionally, they found participants with the greatest activation in the SN/VTA and hippocampus while viewing high curiosity but not low curiosity trivia questions performed better on subsequent face recognition tests. Overall, their results show that curiosity enhances learning even for incidental information and that this improved learning is related to anticipatory activation in reward circuitry and the hippocampus.

1.2.4 Links between curiosity and unsuccessful memory recall

Most research examining the link between memory and curiosity has focused on learning improvements. Emerging evidence suggests there is also a link between curiosity and memory retrieval. Researchers have shown that memory retrieval processes can induce curiosity states that influence subsequent information seeking behaviour. Brooks et al. (2021) found that a metacognitive retrieval experience, namely the feeling-of-knowing (FOK) experience, induces information seeking behaviour as a reflection of curiosity. As described in the overview of the introduction, the FOK experience is a metacognitive state associated with a sense of knowing something without being able to recall it (Hertzog et al., 2010; Koriat, 2000; Souchay et al., 2002). A typical example of this experience was presented as a fictive scenario in the overview. The scenario described a situation where you recognize a person, have a sense you know their name, but cannot quite recall it though you feel you would recognize their name in the future. The familiarity of the cue (i.e., the face in the provided example) and the accessibility of the target (i.e., the name) are both thought to contribute to the FOK experience (Koriat &

Levy-Sadot, 2001). In the case of Brooks et al.'s study, participants were asked to memorize a series of face-name pairs and then, when shown the faces alone, were tested on their recall of the associated names, which for the most part, they did not remember. Brooks et al. then asked participants to provide FOK ratings by judging the likelihood they would recognize the associated names in the future. Brooks et al. then provided participants with limited opportunities to select face-name pairs for restudy to examine how the FOK experience would affect information seeking. They found that faces with higher FOK ratings that were not successfully recalled were more likely to be selected for restudy by participants. Thus, the FOK experience monitors cognitive state and drives subsequent behaviour, specifically motivating information seeking. Therefore, the work of Brooks et al. showed that curiosity, defined broadly as a motivational state to seek out information, is induced by the FOK experience as expressed at the behavioural level via information-seeking behaviour.

Other researchers have found a relationship between curiosity and memory retrieval. They explored the link between curiosity and a metacognitive memory retrieval process similar to the FOK experience, called the tip-of-the-tongue (TOT) phenomenon (Litman et al., 2005; Metcalfe et al., 2017). A TOT experience is similar to a FOK experience in that both involve metacognitive states during recall failures. TOTs are accompanied by an imminent feeling of retrieval (Brown & McNeill, 1966; Schwartz, 2002), whereas FOKs are associated with a feeling that the information will be recognized in the future (Hart, 1965), and the two experiences have been found to activate different brain regions (Maril et al., 2004). Metcalfe et al. (2017) gave participants general knowledge questions and asked them to indicate if the answers were on the tip-of-the-tongue and whether or not they wanted to view the answers at a later time. Participants were told they would only be able to see the answers to up to 10% of the questions. Metcalfe et al. found that participants were most likely to select answers for items they had indicated were on the tip-of-the-tongue, suggesting that the TOT state motivated information seeking and hence induced curiosity. Cleary et al. (2021) found that individuals were more willing to take risks to obtain information when a TOT state had been induced, further demonstrating that TOTs, like FOKs, induce information seeking behaviour and hence induce curiosity. Additionally, Litman et al. (2005) showed participants general knowledge questions and asked them to respond in one of three ways - “I know the answer,” “On the tip-of-the-tongue,” or “I don’t know the answer.” They asked participants to rate how curious they felt about viewing the answers to the questions and allowed them to see the correct answers to as many questions as they pleased during an exploratory phase. They also asked participants to fill out curiosity scales, including a Curiosity as a Feeling-of-Deprivation scale. Litman et al. found that TOT responses, compared to the “Don’t know” and “I know” responses, were associated with the highest curiosity ratings and more information seeking behaviour, demonstrating a link between curiosity and the TOT phenomenon. Additionally, the TOT response was associated with more feelings of uncertainty and tension than either the “I know” or “Don’t know” responses. The feelings of uncertainty and tension present in the TOT response suggest that consistent with the ideas of Berlyne (1960, 1978), autonomic arousal may play a role in the generation of this retrieval-induced curiosity.

1.3 Does autonomic arousal play a role in the generation of retrieval-induced curiosity?

1.3.1 Autonomic arousal and curiosity

According to Berlyne (1960, 1978), curiosity is sparked when uncertainty or lack of information creates an aversive experience, the resolution of which is rewarding. This suggests a potential role for autonomic arousal in the curiosity experience. Empirical evidence has supported the relationship between autonomic arousal and curiosity (Berlyne & Borsa, 1968; Brod & Breitwieser, 2019; Jepma et al., 2012; Kang et al., 2009), as discussed further in this report in section *1.3.3 Empirical support for a role of autonomic arousal in curiosity*. More recently, researchers have built upon the work of Berlyne and further advanced the conceptual framework around the involvement of autonomic arousal in the curiosity experience. Litman (2008, 2010) found that curiosity can involve a sense of deprivation, which can be induced by the feeling of missing an important piece of information, supporting Berylne’s concept that curiosity is an aversive experience. Lowenstein (1994), on the other hand, emphasized that curiosity is motivated by a drive to obtain a reward, with the latter being the missing piece of information. Litman distinguishes between two types of epistemic curiosity, interest and deprivation, which involve a drive to resolve uncertainty but with different feeling states. The former involves satisfaction associated with exploring new ideas, while the latter pertains to seeking specific answers or solutions to missing pieces of information and involves reducing uncomfortable feelings like frustration. Litman (2019) points out that seemingly contradictory theories of curiosity that focus either on resolving a negative experience (i.e., deprivation type), like Berlyne's theory, or emphasizing a drive to obtain a reward (i.e., interest type), like Lowenstein's theory, are indeed compatible. He points out that motivational drives commonly involve both positive and negative states. For instance, hunger and the accompanying drive to eat can be induced by the unpleasant sensation of hunger or by looking at and smelling appetizing food (Lowe & Butryn, 2007). Thus, aversiveness- and reward-based theories of curiosity may not, in fact, be at odds with each other but simply represent different ways the drive associated with curiosity can be induced and different parts of the experience.

1.3.2 What is the physiological basis of autonomic arousal?

Autonomic arousal is a physiological state associated with increased cortical activation, alertness, and a suite of physiological responses like increased heart rate and blood pressure, pupil dilation, slowed digestion and sweating. Numerous brain regions are involved in the control of autonomic arousal, including the brainstem and the cerebral cortex, via connections through the hypothalamus and thalamus (Pfaff, 2018). Activity in the ascending reticular activating system (ARAS) of the brainstem results in the release of excitatory neurotransmitters like norepinephrine, acetylcholine, and dopamine that lead to the autonomic arousal responses, such as an increase in cortical activation and alertness (Iwańczuk & Guźniczak, 2015). The autonomic nervous system regulates involuntary physiological responses, including those associated with the autonomic arousal response (Joshi & Gold, 2020). The autonomic nervous system includes the parasympathetic nervous system (PNS) and the sympathetic nervous system (SNS), two complementary systems that, respectively, are involved in slow and relaxed responses and fast mobilization of energy and attention (Cacioppo et al., 2000; Ulrich-Lai & Herman, 2009). Activation of the SNS is associated with physiological arousal responses such as increases in heart rate and blood pressure, sweating, pupil dilation, and cessation of gastrointestinal peristalsis (Koopman et al., 2011). Autonomic arousal can therefore be measured by measuring changes in these physiological components. Common autonomic measurements include electrodermal activity (Shields et al., 1987), pupil dilation (Loewenfeld, 1993), cardiac rate (McCabe et al., 2000), and respiratory sinus arrhythmia.

The pupil dilation response is widely accepted as a marker of autonomic arousal, particularly when its relationship to variations in luminance is controlled. Non-luminance mediated pupil dilation reflects several cognitive states. Previously pupil dilation response has been associated with reward anticipation (O'Doherty et al., 2003), cognitive effort (Beatty, 1982; Hess & Polt, 1964; Kahneman & Beatty, 1966;), as well as increasing uncertainty and surprise (Lavin et al., 2014). According to Kahneman and Beatty's cognitive load model (Beatty, 1982; Kahneman, 1973; Kahneman & Beatty, 1966), pupil dilation reflects autonomic arousal associated with either voluntary or involuntary allocation of attention, which could broadly encompass several cognitive states, including effort, surprise and reward anticipation. Bradley et al. (2008) measured pupillary response during the viewing of images of different emotional valence and concurrently measured other known markers of autonomic arousal, including skin conductance. They found that pupils were larger when viewing images that were either negatively or positively emotionally arousing than neutral images and that this response covaried with changes in skin conductance. Similarly, Partala and Surakka (2003) found that pupils are larger when listening to positive and negatively arousing auditory stimuli compared to neutral stimuli.

Pupil dilation has been linked to regions of the brain implicated in autonomic arousal, specifically the locus coeruleus (LC) in the brainstem, which contains noradrenergic neurons that release norepinephrine (NE) associated with an autonomic arousal response (Joshi et al., 2020). For instance, pupil size has been found to covary with LC neural firing rates in mice, monkeys, and humans (Joshi et al., 2016; Murphy et al., 2014; Reimer et al., 2016). Joshi et al. (2016) examined the neural correlates of changes in pupil diameter in non-human primates and found a close link to the LC and other brain regions interconnected with the LC. They found that LC activation predicted pupil dilation. Additionally, Murphy et al. (2011) found that measurements of global autonomic arousal covary with pupil response and LC activity in an auditory oddball task where participants were asked to respond to target tones with a finger press. They also found that pupil dilation was related to the P3 component of event related potentials (ERPs) associated with the LC-NE system. Additionally, a study involving pharmacological manipulation (Phillips et al., 2001) of the LC-NE system using adrenoreceptor agonists and antagonists showed that pupil dilation changed in response to these manipulations. Thus, the pupil dilation response has been linked to sympathetic autonomic arousal in studies using behavioural, neural, and pharmacological paradigms. For the remainder of this paper, the consideration of autonomic arousal will focus on pupil dilation as a physiological marker of autonomic arousal.

1.3.3 Empirical support for a role of autonomic arousal in curiosity

There is empirical support for a role of autonomic arousal in the curiosity experience, specifically in relation to pupil dilation and brain activity as measured with electroencephalogram (EEG). Berlyne and Borsa (1968) conducted EEG recordings while showing individuals images that were shown clear and then blurred, as well as images that were shown blurred then clear. EEG results showed greater orientation reactions, in this case, longer desynchronizations, for the blurred to clear order of presentation, or in other words, when uncertainty about the images had been induced. Generally, the orientation response involves automatic attention to novel or uncertain stimuli and is associated with various autonomic arousal responses of the sympathetic nervous system, including, but not limited to, pupil dilation (Lynn, 2013; Sokolov, 1965). Thus, in this case, the induction of perceptual uncertainty was associated with an autonomic arousal response, supporting Berlyne's views on the involvement of autonomic arousal in the curiosity experience. Researchers Jepma et al. (2012) examined the neural correlates associated with both induction and relief of perceptual curiosity. In this case, they conducted fMRIs while individuals completed a similar exercise to the perceptual uncertainty task administered earlier by Berlyne and Borsa, but this time also gave curiosity ratings. Consistent with Berlyne's theory that curiosity is an aversive state and Litman's concept of deprivation curiosity, they found that brain regions associated with autonomic arousal, namely the anterior insula and the anterior cingulate cortex, were activated when curiosity was induced with the presentation of blurred images. In contrast, reward circuitry, specifically parts of the striatum, was activated when curiosity was satisfied by showing the same images unblurred.

Pupillary response associated with relief of curiosity was investigated by Kang et al. (2009). They measured pupil dilation response while participants anticipated and viewed the answers to trivia questions they had also rated in curiosity. They found that pupil dilation was greatest for trivia questions rated higher in curiosity at about 1 second before the answers were presented and during answer presentation. Given the link between pupil dilation and autonomic arousal, this study suggests that autonomic arousal may be involved not only in the induction of curiosity, as suggested by brain activity findings of Jepma et al. (2012), but also both in the anticipation of the relief of curiosity (i.e., when anticipating the answers to trivia questions) and during the relief itself (i.e., when viewing the answers). Previously, pupils had been shown to dilate when individuals anticipate receiving a reward (O'Doherty et al., 2003). Kang et al. interpreted their pupillary results as consistent with both the ideas that curiosity is the anticipation of rewarding information and enhances the learning of new information.

Brod and Breitwieser (2019) measured pupil dilation while participants anticipated and viewed the answers to numerical fact-based questions. After showing participants the questions, before revealing the answers, they had participants either make predictions about the answers or provide relevant examples and provide a curiosity rating about each question. Making predictions was associated with higher self-reported curiosity about the questions compared to the example condition. Brod and Breitwieser found pupils dilated more when participants anticipated the answers to questions they had rated higher versus lower in curiosity. Pupil dilation was also greater for the prediction condition compared to the example condition, both when anticipating the answers to questions and while viewing the answers. However, pupil dilation was greatest for items rated high in curiosity where predictions had also been made. They interpreted these results as supporting the notion that the noradrenergic autonomic arousal response is associated with curiosity and that the degree of dilation during anticipation may be an indicator of the strength of the curiosity experience. They suggested that making a prediction could increase the perceived value of information or relevance of the knowledge gap, which could, in turn, increase autonomic arousal associated with both anticipating the response as well as reflecting increased awareness of the knowledge gap. Additionally, they suggested that the increased dilation when viewing the answers to questions, specifically when predictions were made, could reflect an increase in surprise that would be present when viewing an outcome different than what was expected.

Further, in the same study, Brod and Breitwieser (2019) related their pupillary results to the memory-enhancing effects of curiosity. They tested subsequent recall and found that answers to questions rated higher in curiosity, which had also been associated with greater pupil dilation and hence greater autonomic arousal, were remembered better than questions rated lower in curiosity. Brod and Breitwieser postulated that it is possible the increase in autonomic arousal associated with the curiosity experience could contribute to the learning enhancements observed when curiosity is induced, given that the excitatory neurotransmitter, noradrenaline, results in increased cortical sensitivity and activation (Aston-Jones & Cohen, 2005).

1.3.4 Pupil dilation in relation to memory retrieval

In addition to the link established between pupillary response and the memory enhancing effects of curiosity, the pupillary response has been investigated in relation to memory retrieval. Most studies have examined pupil dilation in relation to individuals exposed to familiar (i.e., previously studied) versus unfamiliar non-studied items. Several researchers found that pupils dilate more upon viewing previously studied items in such comparisons (Gardner et al., 1974; Goldinger & Papesh, 2012; Heaver & Hutton, 2011; Naber et al., 2013; Papesh et al., 2012; Võ et al., 2008), a finding commonly referred to as the ‘old-new’ effect. However, these findings are not concerned with metacognitive retrieval experiences.

Ryals et al. (2021) examined pupil dilation during a TOT state, a metacognitive retrieval experience similar to FOK. To understand the potential involvement of autonomic arousal, Ryals et al. examined pupil dilation responses in TOT experiences tied to unsuccessful word retrieval. They asked participants to attempt to answer general knowledge questions while measuring their pupil responses. After posing each question, they asked participants to indicate whether or not they had experienced a TOT state and to rate the strength of the TOT experience. They also asked participants to type out the answers to questions if they knew the answers. Ryals et al. found that dilation was greater when participants viewed questions that had elicited a TOT state compared to questions that had not elicited a TOT state. Ryals et al. interpreted their results as demonstrating that autonomic arousal and excitement are part of the TOT experience, given that greater dilation was present in a TOT state compared to a non-TOT state. Ryals et al. did not examine information seeking behaviour like Brooks et al. (2021) and so did not directly link the TOT state to curiosity. However, even though Ryals et al. did not probe any relationship to curiosity, given the previous links between TOT states and information seeking and hence curiosity (Litman et al., 2005; Metcalfe et al., 2017), their findings that autonomic arousal is present in a TOT state, are still consistent with the ideas of Berlyne (1954) who suggested that curiosity is an aversive experience.

1.4 Current study

1.4.1 Study aims and goals

The current study aimed to explore the role of autonomic arousal in curiosity induced by unsuccessful memory recall and to determine whether subsequent access to the information that could not be recalled is experienced as rewarding. Previous research established a strong link between curiosity and long-term declarative memory, showing that curiosity enhances encoding and consolidation of information (Brod & Breitwieser, 2019; Galli et al., 2018; Gruber et al., 2014; Kang et al., 2009; Marvin & Shohamy, 2016; Stare et al., 2018). Emerging research provided a link between curiosity and memory retrieval (Brooks et al., 2021; Litman et al., 2005; Metcalfe et al., 2017). In their work on metacognitive retrieval experiences, Brooks et al. (2021) demonstrated that unsuccessful memory recall sparks curiosity by way of influencing subsequent information seeking. However, they did not examine the role of autonomic arousal in the curiosity experience, nor did they explore the role of reward. Previous research has shown a link between autonomic arousal and curiosity (Brod & Breitwieser, 2019; Kang et al., 2009), as well as between reward anticipation and curiosity (Gruber et al., 2014; Kang et al., 2009; Marvin

& Shohamy, 2016). However, researchers have not examined the role of autonomic arousal in the induction of epistemic curiosity, nor did they explore autonomic arousal in curiosity induced by unsuccessful memory recall, and how this relates to metacognitive retrieval experiences and subsequent reward anticipation.

The current work aimed to examine pupil dilation responses during the FOK experiences, including the induction and resolution of the experiences, for the purpose of understanding the role of autonomic arousal in curiosity induced by unsuccessful memory recall. Further, it aimed to examine if subsequent access to the unsuccessfully recalled information is experienced as rewarding. The study addressed a potential role of autonomic arousal both when the generation of a FOK state induces curiosity, and during the anticipation of the relief of the curiosity experience when the FOK state is about to be resolved. To test this, the FOK paradigm previously applied by Brooks et al. (2021) involving familiar and novel faces as stimuli was adapted. Brooks et al.'s paradigm was combined with autonomic recording, using the pupillary response as a marker of autonomic arousal. Participants first studied face-name pairs in a learning phase (Phase 1 - Encoding). Next, they were shown the previously seen faces and new 'lure' faces and asked about their ability to recall the accompanying names before being asked to rate their FOK experience for each face (Phase 2 - Recall Attempt and FOK Judgment). Finally, participants were given limited opportunities to view face-name pairs together again, and they were asked to rate their satisfaction upon seeing these face-name pairs (Phase 3 – Information Seeking and Satisfaction Rating). Pupil dilation response was measured in Phases 2 and 3 with a pupilometer.

1.4.2 Hypothesis

Conceptually, this study examined both the induction and anticipation of the relief of epistemic curiosity. Guided by Berlyne's influential theory on curiosity, the study tested the hypothesis that autonomic arousal is a part of the curiosity experience induced by unsuccessful memory recall. Further, it tested whether subsequent access to the information that could not be recalled is experienced as rewarding, particularly for items that induced greater curiosity, and whether autonomic arousal plays a role in the anticipation of the relief of curiosity.

1.4.3 Predictions

If curiosity is an aversive state, as theorized by Berlyne (1954), one would expect that the pupil dilation response will increase as FOK ratings increase in Phase 2, reflecting higher levels of induced curiosity and corresponding levels of autonomic arousal. Furthermore, pupil dilation at the time curiosity is induced was expected to be associated with later information seeking behaviour, with faces that elicit greater pupil dilation during the FOK experience also being selected more for restudy. This is because, consistent with Berlyne's views, one would expect that individuals would be motivated to resolve the aversive state of the curiosity experience.

Further, it was expected that subsequent access to the information that could not be recalled would be experienced as rewarding, particularly for items that induced greater curiosity. Thus, it was expected that individuals would feel more satisfied when viewing face-name pairs in Phase 3 for faces they had rated higher in FOK during Phase 2. Additionally, it was expected that autonomic arousal would play a role in the anticipation of this reward, such that pupil dilation would be greater when participants expected that their curiosity would be resolved. Namely, it was expected that during the Phase 3 information seeking period, pupils would dilate more when participants viewed faces they selected for restudy, that is, while they would be anticipating having their curiosity satisfied, compared to viewing faces they did not select for restudy.

Methods and Results

2 Experiment

2.1 Methods

2.1.1 Participants

Approval for the experiment was obtained from the Non-Medical Ethics Board at the University of Western Ontario. Participants were 58 individuals between the ages of 18 and 35 (average age = 20.41; 41 females and 17 males) who were fluent in English with normal to corrected-to-normal vision. Participants were undergraduate students at the University of Western Ontario compensated with credits required for their coursework recruited through the psychology research participation pool SONA system. They were also London, Ontario community members as well as graduate students at the University of Western Ontario, recruited through the OurBrainsCAN research pool and provided with monetary compensation for participating in the study. A total of 19 participants were excluded due to technical problems (n = 3), lack of compliance with instructions (n = 4), or having insufficient trials in critical experimental conditions to allow for reliable statistical estimates (n = 12). To ensure there were enough trials per condition for reliable statistical analyses, we required at least 10 trials per experimental condition after pupillary pre-processing. Of the 19 excluded participants, 11 were excluded for not meeting this criterion. An additional participant was excluded for not having at least 4 trials per each two-way ANOVA condition (e.g., trials rated high in FOK and selected for restudy), which was the minimum number of trials required for the ANOVA analysis to run in RStudio. Three more participants were discarded due to technical problems with the pupilometer. An additional four were excluded for problematic participant responses. For instance, two participants indicated they recalled more than two standard deviations above the mean level of participant recall (M = 10.92, SD = 15.78), an unlikely level of recall for the experimental task. After applying exclusion criteria, the data of 39 participants were included in the analyses.

2.1.2 Materials

Stimuli were 104 faces, neutral in expression and of average attractiveness, pseudo-randomly selected from the Chicago Face Database (Ma et al., 2015). Faces were selected that achieved a rating of less than 3.5 on a 7-point scale on emotionality (i.e., fear, sadness, surprise, disgust, threat, happiness, and anger) as well as ratings between 2 and 5 on a 7-point scale of attractiveness. Of the 104 faces, 52 were male (12 African-American, 40 Caucasian), and 52 were female (12 African-American, 40 Caucasian). At the start of the experiment, the 52 female faces and 52 male faces were each randomly shuffled, and the first 39 faces of each group were used in Phase 1, and the remaining 13 were used as lure faces in Phase 2. The faces were paired with English names selected from the U.S. Census Bureau 1990 (https://catalog.data.gov/dataset/names-fromcensus-1990). First names and surnames combined were 9 to 14 characters in length (M = 11.98, SD = 0.83) and were of a syllable count of 3 to 6 syllables (M = 3.97, SD = 0.54). Names included 52 full male names and 52 full female names. Each group of names was randomly shuffled before pseudo-randomly assigning the names to the 104 faces used in the experiment, matched by sex.

2.1.3 Procedure

Psychophysics Toolbox Version-3 (http://www.psychtoolbox.org/) and MATLAB R2019b (The MathWorks, Natick, MA) were used to run the experiment. The experiment was displayed on a 21-inch LCD Asus monitor running on 1,024 X 768 pixels resolution.

2.1.3.1 Behavioural paradigm

General Set-Up: The stimuli were presented to participants in a single experimental session lasting 60 to 90 minutes in length over the course of three phases: Phase 1 – Encoding, Phase 2 – Recall Attempt and FOK Judgment, and Phase 3 – Information Seeking and Satisfaction Rating. Each phase was preceded with a set of instructions describing the task in detail, including what judgments and key presses would be required. Pupillary responses were recorded with a camera in Phases 2 and 3 of the experiment as detailed in *Section 2.1.3.2 – Pupil response measurement*. Before the experiment began, to keep the pupil within the camera's view, participants were instructed to maintain their gaze in the centre of the monitor as much as possible and to avoid looking down at the keyboard each time they made their selections with key presses. This was intended to improve the quality of the collection of pupillary data, given that looking down at the keyboard or away from the screen during the experiment could cause pupil occlusion by the eyelid. Stimuli and text were presented on white backgrounds and presented to participants on the monitor before them.

Phase 1 – Encoding: In this phase, participants were presented with a series of 78 face-name pairs for 3 seconds per item and were asked to memorize each face-name pair (Figure 1). A black fixation cross was displayed on a blank screen for 0.5 seconds.

Phase 2 – Recall Attempt and FOK Judgment: Participants were shown 104 faces, comprised of 78 faces previously seen during Phase 1 and 26 novel or previously unseen faces. Having familiar and novel faces allowed for the manipulation of familiarity, which has been shown to influence FOK judgments (Brooks et al., 2021; Koriat & Levy-Sadot, 2001). Participants were not told that new, previously unseen faces had been added to this phase of the experiment.

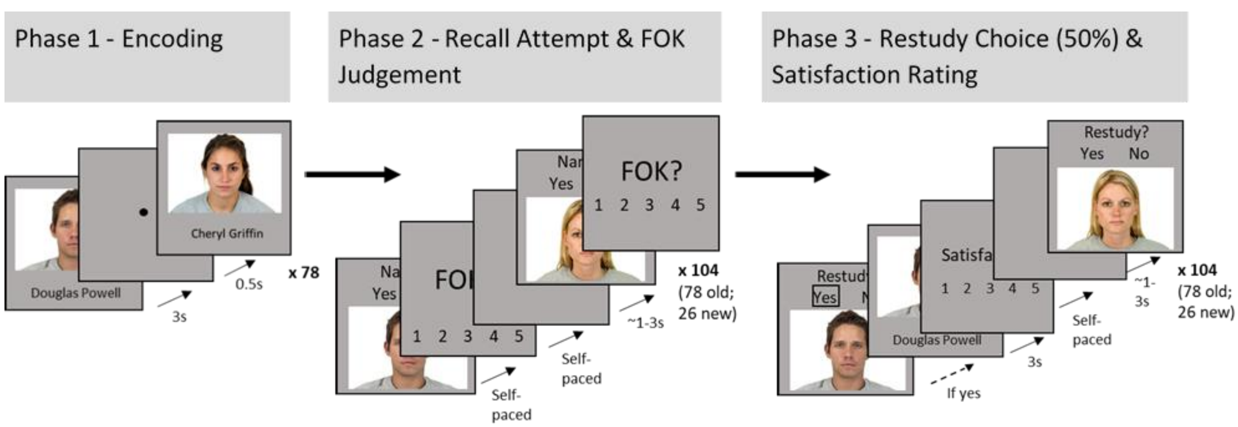

Figure 1. **Experimental paradigm showing the three phases of the study.**

Since the experiment was meant to probe FOK in the absence of successful recall, trials with success or partial success were identified for removal. This was achieved by asking participants explicitly if they recall the name for a face before being asked to make a FOK judgment. For each face, participants were first asked, “Can you remember the person's full name?" and were asked to indicate their response with a key press, specifically selecting the up arrow for 'yes' and the down arrow for 'no'. Following the recall test, participants made a FOK judgment about that same face by indicating on a 5-point Likert scale the likelihood they would be able to recognize the name in the future. Participants were asked to indicate with a key press, "How likely is it that you would correctly recognize their name? Use a 1 to 5 scale where 1 = very unlikely and 5 = very likely." The time allowed to provide a recall judgment and the FOK rating were both self-paced. Between each trial, a black fixation cross was displayed on a blank screen for between 1 and 3 seconds, on average 2 seconds.

Phase 3 – Information Seeking and Satisfaction Rating: In this phase, participants were provided with a limited number of opportunities to seek out information about face-name pairs. Specifically, they were given the ability to select up to one-half (or 52) of all of the faces shown to view the associated name pairing. During this phase, participants were shown the same 104 faces they were previously shown in Phase 2 – Recall Attempt and FOK Judgment. For each face, they were asked, "Would you like to see their name again?" and to indicate a yes response with an up arrow and a no response with a down arrow. A tally of how many of the 52 face-name pair selections remained was displayed at the bottom right-hand side of the screen. If participants selected a face, they were given 3 seconds to view that face paired with its name. After choosing a face-name pair, participants were asked, "How satisfied were you when you saw the face and name together again?" with 1 being not at all satisfied and 5 being very satisfied. The satisfaction rating provided a measure of intrinsic reward, which is an expected experience upon having epistemic curiosity satisfied (Marvin & Shohamy, 2016). Both the information seeking opportunity and satisfaction rating were self-paced. Between each trial, a black fixation cross was displayed on a blank screen for between 1 and 3 seconds, on average 2 seconds.

2.1.3.2 Pupil response measurement

2.1.3.2.1 Recording

During Phases 2 and 3 of the experiment, the pupillary responses of the right eye were tracked using an EyeLink 1000 Tower Mount system (SR Research Ltd.) with a 25 mm lens. The sampling rate was set to 1000 Hz. Participants were seated at a distance of 57 cm from the monitor, and their heads were stabilized in the chin and forehead rests of the Tower Mount system. To optimize the pupillary recording, the camera lens was focused for each participant and pupillary, and corneal reflection thresholds were adjusted if needed. Before the experiment began, each participant was asked to complete a nine-point standard calibration and validation task, which involved following a moving point on the screen with their gaze. The experiment took place in a dimly lit room, with ambient light set to approximately 1.6 foot-candles, measured using a YFE Digital Light Meter Yu Fong Lux Hi Tester YF – 1065F. Because pupil responses are sensitive to changes in light levels, face images were luminance matched in MATLAB using SHINE_colour, an adaptation of SHINE Toolbox for colour images (Dal Ben, 2021).

2.1.3.2.2 Preprocessing

Pupillary data were pre-processed in MATLAB to remove artifacts following the guidelines and applying the code described by Kret and Sjak-Shie (2019). Invalid pupil samples were removed from the raw data, including those with negative values or those identified as invalid by the EyeLink system, and the data were converted to a standard format that included raw pupil dilation in arbitrary units across time together with the experimental messages for each trial. Artifacts were removed from the data from each participant in a series of steps, and the remaining data were smoothed and interpolated, described in more detail in the paragraph below.

A series of steps were applied to remove artifacts and smooth the collected pupillary data for each participant. The speed of change in dilation between actual dilation and constriction is typically less than the speed of change that occurs during events like blinking or occlusions from eyelids (Kret & Sjak-Shie, 2019). Thus, to remove invalid samples, samples with a rate of dilation change greater than a threshold value were removed. The threshold value for each participant was determined by multiplying the median absolute deviation (MAD) of dilation speed by a constant value and adding that to the median dilation speed. Clusters of pupillary samples resistant to dilation speed filtering that are outliers from the absolute trend line were also removed. Following this, remaining blinks and physical disturbances were addressed by removing segments of pupillary data with gaps greater than 75 ms, as well as the 50 ms of samples preceding and following each 75 ms gap. A sparsity filter was also included that splits samples where gaps were larger than 40 ms and then removed the resulting sections smaller than 50 ms. The remaining data were smoothed and interpolated. Samples falling outside a minimum and maximum range were removed, specifically, samples with pupil size falling below 1.5 mm and above 9 mm, as suggested in by Kret and Sjak-Shie (2019), following the method applied by Kret et al., 2014. The EyeLink 1000 records pupil dilation response in arbitrary units. To transform the pupillary recording from arbitrary units to millimetres, pupil dilation was measured with an artificial eye of known pupil diameter placed at participant eye level in the Tower Mount. A calibration factor was then computed using the resulting measurement and applied to the pupillary data to identify samples of the specified minimum and maximum size. For each participant, trials with more than 30% of data loss after applying these procedures were rejected from the analysis. Furthermore, trials with judgment times greater or less than two median absolute deviations were removed for each participant.

The mean pupil diameter was estimated over the full duration of response times for the periods of interest in Phases 2 and 3 from the valid samples after the preprocessing procedure was applied. Pupillary data for each participant were baseline corrected by subtracting the average pupillary signal 200 ms before stimulus onset for each trial.

2.1.4 Analytical approach

To understand the relationships between variables for the behavioural results, we conducted t-tests and correlational analyses. This included gamma correlational analysis to evaluate the relationship between FOK ratings and subsequent information seeking behaviour, and Spearman correlational analysis to examine the relationship between resolution of FOK states and reward. To examine pupillary results, two-way analysis of variance (ANOVA) was primarily utilized as an analytical method. Specifically, two-way ANOVA was used to examine if pupillary responses during the recall attempt and FOK experiences are associated with FOK ratings and subsequent restudy choice. Additionally, two-way ANOVA was performed to examine if pupillary response during Phase 3, when participants were selecting faces for restudy of face-name pairs, is associated with FOK ratings and information seeking behaviour.

2.2 Results

2.2.1 Behavioural results

2.2.1.1 Validity of FOK ratings in the current behavioural paradigm

Cue familiarity has previously been shown to influence FOK ratings, with more familiar items being rated higher in FOK experience (Brooks et al., 2021; Koriat & Levy-Sadot, 2001). We could therefore examine the validity of the FOK ratings in our experimental paradigm by verifying their sensitivity to a familiarity manipulation. Of the 104 faces shown in Phase 2 and then again in Phase 3, one-quarter (or 26 faces) were lure or novel faces that had not actually been paired with names for memorization during the encoding period in Phase 1. The other three-quarters (or 78 faces) were familiar faces that had been previously studied in Phase 1. Therefore, we could compare FOK ratings between familiar and novel faces and expect to find higher mean FOK ratings for familiar faces if the FOK ratings were valid. Indeed, we found that the average FOK ratings for familiar faces (M = 2.45, SD = 0.34) were significantly higher than those for novel faces (M = 1.85, SD = 0.47), $t(38) = 9.60$, $p < .001$, $d = 1.46$, consistent with previous findings.

Note that faces were only included in the above validity analysis for each participant if the participant had indicated in Phase 2 that they could not successfully recall the name associated with that particular face. Reported unsuccessful recall for all participants ranged between 71 (i.e., 68%) and 104 (i.e., 100%) of the names. Of all participants, 23 indicated they did not successfully recall 100 or more of the names. On average, participants could not successfully recall 96.3 names of the 104 faces shown (SD = 10.12). A FOK experience involves not being able to recall information while simultaneously feeling that this information is known and will be recognized in the future. Therefore, recall of the name would confound the FOK experiences. As such, trials with successful recall were not included in this and subsequent analyses.

2.2.1.2 Relationship between FOK ratings and subsequent information seeking behaviour

With our primary focus on curiosity, we examined whether FOK ratings (Phase 2) would predict participant selection of face-name pairs during restudy (Phase 3), similar to the findings of Brooks et al. (2021). In Phase 3, participants were shown the 104 faces they had previously seen during Phase 2 and were given the opportunity to select up to one-half or 52 of these faces to view the associated face-name pairs. Providing participants with a limited number of opportunities to select faces for restudy allowed us to evaluate the information seeking preferences of participants.

Our results showed that participants are more likely to choose face-name pairs for faces that had been given higher FOK ratings (Figure 2). The mean gamma correlation between FOK and information seeking choices for trials with no successful recall was significantly greater than zero (*Mean gamma* = 0.36, SD = 0.25, $t(38) = 9.09$, $p < .001$). This result is consistent with the previous findings of our lab, showing that FOK experiences predict to what extent participants will subsequently seek information and hence whether they are sparking curiosity.

We also examined if FOK ratings predict information seeking behaviour, focusing our analyses only on familiar items (i.e., excluding the “novel” faces first introduced during Phase 2). Because familiar items are rated higher in FOK, we wanted to evaluate if the FOK ratings would still predict information seeking behaviour when prior exposure to the cues (faces) is held constant. The mean gamma correlation between FOK and information seeking choices was significantly greater than zero (*Mean gamma* = 0.42, SD = 0.25, $t(38) = 10.49$, $p < .001$) in this case as well. Our results confirm that FOK ratings predict information seeking behaviour independent of familiarity and that it is not the experimentally induced familiarity alone that drives this relationship.

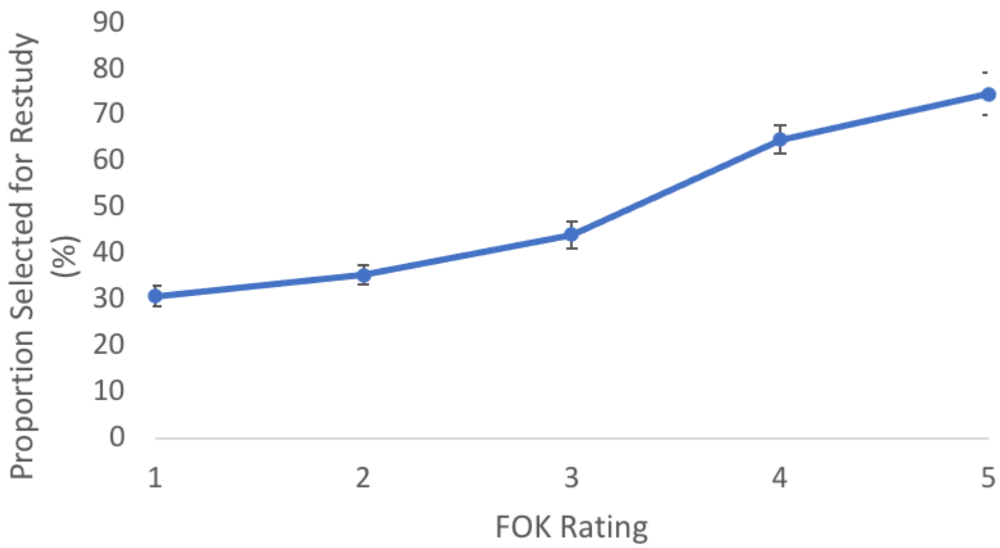

Figure 2. **Average proportion of trials selected for information seeking as a function of FOK rating (on a 5-point Likert scale) for all participants, specifically for trials with unsuccessful recall of face-name pairs. Error bars represent the standard error of the mean (SEM) for the average proportion of trials selected.**

2.2.1.3 Resolution of FOK states and reward

During Phase 3, participants were asked to rate their satisfaction on a 5-point Likert scale after viewing face-name pairs for faces they selected when making their information seeking decision. To understand if the level of satisfaction experienced was related to the level of curiosity, we examined if satisfaction upon viewing face-name pairs was tied to earlier FOK experiences (when curiosity was induced). To do so, we ran a Spearman correlational analysis for each participant between their FOK ratings in Phase 2 and their satisfaction ratings during Phase 3. We then conducted a t-test to see if the average correlation for participants was significantly different from zero.

Participants were more satisfied upon viewing face-name pairs (i.e., faces they selected during Phase 3) for faces they had rated higher in FOK during Phase 2. There was a positive correlation (*Mean rho* = 0.24, SD = 0.21) between satisfaction ratings and FOK ratings, which was found to be larger than zero, $t(38) = 9.45$, $p < .001$. These results suggest that it is more rewarding to be exposed to information that could not be previously recalled when high FOK experiences accompanied this unsuccessful recall.

2.2.2 Pupillary analysis

2.2.2.1 Pupillary response during induction of curiosity with unsuccessful memory recall

Our behavioural analyses demonstrate that curiosity is induced by FOK experiences. We wanted to examine any potential role of autonomic arousal in this curiosity and how this relates to later information seeking behaviour. To do so, we ran a series of analyses that focused on the relationship between pupillary response in Phase 2 (when participants made their recall attempts and FOK judgments) and later selection of face-name pairs in Phase 3.

In our first set of analyses, we measured pupillary responses in Phase 2 when participants made their FOK judgments. Our behavioural results show that FOK experiences during Phase 2 are correlated with the information seeking behaviour in Phase 3 and, therefore, that the FOK experiences may be inducing curiosity. We could therefore examine the relationship between autonomic arousal and the induction of curiosity by measuring pupillary responses during the FOK experiences. Specifically, we compared pupil dilation at different levels of induced curiosity by comparing pupillary responses at high and low levels of FOK ratings. FOK ratings were factorized into ‘high’ and ‘low’ conditions, with ‘high’ including responses 3, 4, and 5 on the 5-point Likert scale, and ‘low’ including responses 1 and 2. FOK ratings were divided this way on account of highly right-skewed response distributions. After pupillary pre-processing, there were only 29.41 trials on average (SD = 10.92) across participants in the FOK ‘high’ condition compared to 51.85 trials on average (SD = 12.34) in the FOK ‘low’ condition. We measured pupil dilation for each trial from the time participants were asked to indicate their FOK rating to when they provided their FOK rating response with a key press (i.e., 1, 2, 3, 4 or 5). The mean pupil diameter was estimated for each participant for the full duration of each trial during this FOK rating period, not including the recall attempt, after applying the pupillary preprocessing procedure described in the Methods section of this paper. The mean pupillary values were then standardized for each participant. The pupillary analyses were restricted to trials where participants had unsuccessful recall. Our results show that mean pupillary response was greater for items rated high in FOK (M =

32.53, SD = 205.03) compared to items rated low in FOK (*M* = -55.96, SD = 166.40), $t(38) = 2.88$, $p = .0064$. These results suggest that autonomic arousal was greater for faces that generated higher levels of curiosity, indicated by higher FOK ratings, at the time curiosity was induced.

To ensure that the observed difference in pupil dilation between high and low FOK trials was not a reflection of binarizing the ratings, we also conducted a correlational analysis between FOK ratings and pupil response. We computed the correlation between FOK ratings on the 5-point Likert scale and mean standardized pupillary responses during Phase 2 for each participant during the period when participants made their FOK judgments. We found there is a positive correlation between FOK rating and pupillary response (*Mean rho* = 0.16, SD = 0.16). The mean Spearman correlation was larger than zero ($t(38) = 6.20$, $p = <.001$), indicating that there is a significant positive relationship, such that when FOK rating values increase, mean standardized pupil dilation response increases as well. These findings are consistent with those obtained with binarized values, but they also indicate that the difference in pupil dilation response observed in the FOK ‘high’ vs ‘low’ conditions in the previous t-test analyses was not due to binarization.

2.2.2.1.1 FOK pupillary response and subsequent information seeking

Having established that the observed relationship between pupillary response and FOK ratings is not a result of the binarization of FOK ratings, we conducted additional analysis with binarized FOK values, given the highly right-skewed response distributions. Specifically, we next examined if the pupillary response during the FOK experiences, at the time of curiosity induction, is not only positively associated with FOK ratings but also associated with the selection of face-name pairs during Phase 3. This would enable us to evaluate whether autonomic arousal at the time of curiosity induction is also linked to subsequent information seeking behaviour. To address this question, a two-way ANOVA was performed to examine the main effects of FOK ratings and information seeking behaviour, and their interaction, on pupil dilation during the FOK judgment period in Phase 2, not including the recall attempt. Setting up the analysis in this way allowed us to examine whether or not pupillary response at Phase 2 differed depending on whether or not a face was subsequently selected for restudy during Phase 3 and on

FOK ratings. Standardized mean pupillary responses were prepared in the same way described for the t-test comparison, and FOK ratings were similarly binarized. Information seeking choices included those faces later selected during the information seeking phase (information seeking ‘yes’) and faces not selected (information seeking ‘no’). We also conducted a mixed-effects model analysis to examine if the pupillary response at Phase 2 would predict information seeking behaviour and if this was related to FOK rating. The results of this modelling are consistent with the two-way ANOVA results. However in the interest of brevity, this analysis has not been included in this report.

Phase 2 mean pupil dilation across time for all participants for FOK ‘high’ and FOK ‘low’ ratings during the FOK judgment period of Phase 2 is shown in Figure 3. Consistent with the findings of our t-test, there was a significant main effect for FOK ratings for the FOK judgment period of Phase 2, such that mean standardized pupil dilation was greater for faces rated higher in FOK (M = 32.53, SD = 205.03) versus those rated lower in FOK (M = -55.96, SD = 166.40), $F(1, 38) = 17.41$, p = < .001. However, the main effect of information seeking behaviour was not significant. There was no significant difference in pupillary response between faces that were later selected (information seeking ‘yes’, M = -11.30, SD = 198.98) and faces that were not selected (information seeking ‘no’, M = -42.96, SD = 155.80), $F(1,38) = 2.06$, $p = .16$. The interaction term was also not significant, $F(1,38) = 0.95$, $p = .95$. These results suggest that autonomic arousal, as reflected in the pupillary response, is associated with metacognitive experience tied to induction of curiosity but not to later information seeking.

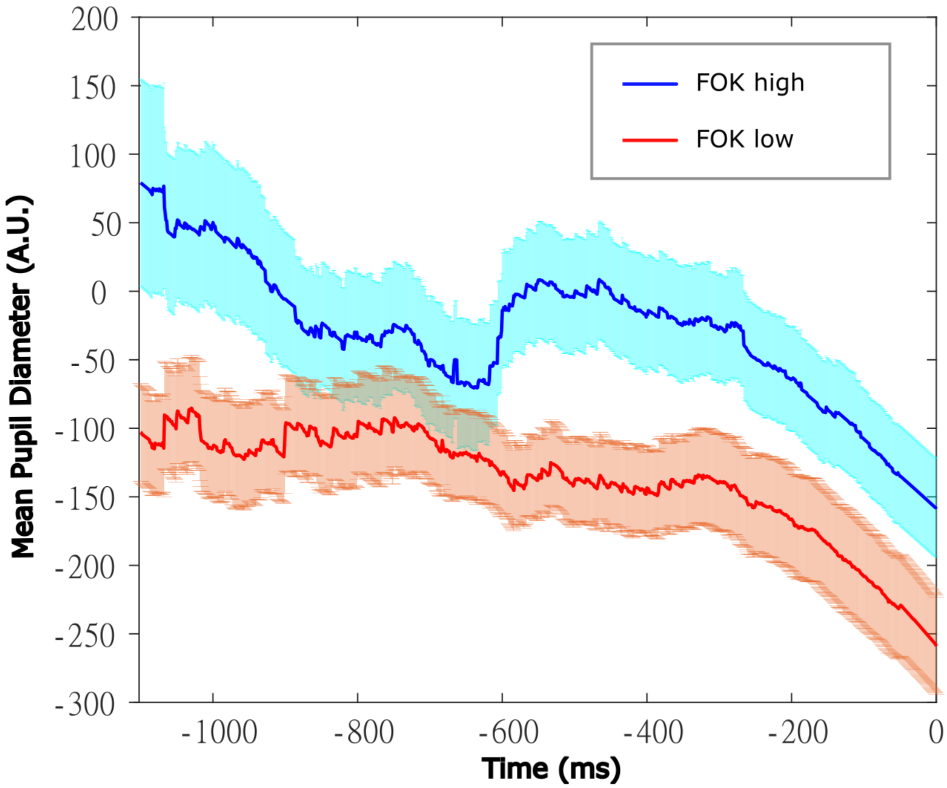

***Figure 3.* Baseline corrected mean pupil dilation (arbitrary units) in Phase 2 of the experiment, specifically during the FOK rating period, across all participants over time (ms) for faces rated high in FOK (i.e., rated 3, 4, or 5 on a 5-point scale) versus faces rated low in FOK (i.e., rated 1 or 2 on a 5-point scale). Standard error bars are represented in cyan around FOK high ratings and in light red for FOK low ratings. Note that the figure is response-locked, showing mean pupil dilation before and up to the point when participants made their FOK judgments at time '0'.**

2.2.2.1.2 Timing of pupillary response at curiosity induction

We wanted to know when the observed relationship between pupillary response and FOK ratings emerged in the experimental paradigm. The results of our t-test demonstrate that FOK ratings are positively associated with pupillary response at the time of the FOK experience when participants made their FOK ratings. Pupillary response was measured throughout Phase 2, which included two memory judgments, a recall attempt and a FOK rating. To determine if the relationship between FOK ratings and pupillary response was present before participants made their FOK ratings, we evaluated if FOK ratings are also associated with pupillary responses at the time of the recall attempt in Phase 2, which in the experimental procedure, occurred before the FOK judgment. Additionally, we were interested in evaluating if information seeking behaviour during Phase 3 would be linked to pupillary response at this earlier time when participants were making their recall attempts.

A two-way ANOVA was performed to examine the main effects of FOK ratings and information seeking behaviour, and their interaction, on pupil dilation in Phase 2, for the recall attempt period. Inputs of FOK ratings and information seeking choice were the same as those described for the previous two-way ANOVA, and pupil responses were standardized in a similar way. Again, setting up the analysis in this way allowed investigation of whether or not pupillary response at Phase 2, in this case during the recall attempt period, differed depending whether or not a face was subsequently selected for restudy during Phase 3 and on FOK ratings. No significant main effects or interaction was found for the recall period of Phase 2. There was no significant difference in pupillary response between faces rated high in FOK (M = 349.08, SD = 291.33) and faces rated low in FOK (M = 209.57, SD = 227.18), $F(1,38) = 1.80$, $p = .19$. Similarly, there was no significant difference in pupillary response between faces that were later selected (information seeking 'yes', M = 328.88, SD = 281.27) and faces that were not selected (information seeking 'no', M = 311.17, SD = 228.06), $F(1,38) = 2.06$, $p = .16$. Furthermore, the interaction term was not significant, $F(1,38) = 0.13$, $p = .72$.

These results suggest that the difference in pupillary response observed between the FOK high and low conditions is associated with the metacognitive retrieval attempts during the FOK experiences, but not the earlier recall attempt, and that later information seeking during Phase 3 is not significantly related to pupillary response at any period of Phase 2.

We wanted to determine if there is an association between FOK and pupillary response that is independent of the familiarity of the cue, in this case, being the familiarity of the face. Cue familiarity has previously been shown to influence FOK ratings (Brooks et al., 2021; Koriat & Levy-Sadot, 2001). In our study, average FOK ratings were significantly higher for familiar faces compared to novel faces for faces that were not successfully recalled, as described in this report in Section 2.2.1.1. This raises the question of whether the positive relationship between FOK ratings and pupil dilation response in Phase 2 during the FOK judgment period is actually due to the familiarity of the cue (face) rather than the metacognitive retrieval experience. To answer this question, we conducted a two-way ANOVA examining the main effects of FOK ratings and information seeking behaviour, and their interaction, on pupil dilation in Phase 2 for the FOK judgment period. Critically, we restricted the analysis to trials with familiar faces in order to determine if FOK ratings were still positively associated with pupil dilation response even when the familiarity of face status was held constant. FOK ratings were binarized into FOK 'high' and 'low' ratings, similar to the previous analyses, and trials were restricted to those with unsuccessful recall. Our results show there was still a significant main effect for FOK ratings, such that mean standardized pupil dilation was greater for faces rated high in FOK (M = 35.83, SD = 224.30) versus those rated low in FOK (M = -61.63, SD = 183.66), $F(1, 38) = 11.74$, $p = .0015$. Similar to the analysis including trials with both familiar and novel items, the main effect for information seeking behaviour and the interaction term were not significant for the judgment period. These results show that it is not the familiarity of the face cue that is driving the main effect of FOK ratings on pupillary response when participants are making their FOK judgments, but rather the relationship reflects the sensitivity of the pupillary response to FOK ratings more generally.

2.2.2.2 Pupillary response and relief of curiosity induced by unsuccessful memory recall

Our previous analyses focused on pupillary response during the induction of curiosity, which in this experimental paradigm occurred during the FOK experiences. We also wanted to examine the relationship between pupillary response and the relief of curiosity, occurring during Phase 3 – Information Seeking and Satisfaction Rating. Specifically, we examined pupillary responses during the anticipation of the relief of the curiosity experiences. We did so by measuring pupil dilation when participants were choosing which face-name pairs to view again when considering faces in Phase 3 and conducting statistical analyses to understand how information seeking behaviour and FOK ratings influenced pupillary responses during this period.

In the experimental paradigm, if participants selected a face during Phase 3, they were subsequently shown the associated face-name pair for 3 seconds. To understand if autonomic arousal when anticipating the relief of curiosity is influenced by the induction of curiosity, we evaluated whether pupil dilation responses at Phase 3 during this information seeking period, were influenced by the earlier FOK ratings when curiosity was induced.

Conducted in the same way as our previous analyses, a two-way ANOVA was performed to examine the main effects of FOK ratings and information seeking behaviour, and their interaction, on pupil dilation in Phase 3 when participants were making their choices about which faces to select for viewing of face-name pairs. We found there was a significant main effect for information seeking behaviour, such that pupil dilation was greater for faces selected for viewing of face-name pairs (*M* = 241.93, SD = 265.43) compared to those not selected (*M* =149.60, SD = 191.99), $F(1, 38) = 10.41$, $p = .0026$. Mean pupil dilation across time for all participants for faces selected versus faces not selected during Phase 3 is shown in Figure 4.

The main effect of FOK ratings was not significant (FOK 'high' (*M* = 231.03, SD = 219.77), FOK 'low' (*M* =196.48, SD = 212.72), $F(1, 38) = 0.0077$, $p = .93$, nor was the interaction term, $F(1, 38) = 0.42$, $p = .52$. These results indicate that pupillary response is greater when participants are anticipating the relief of their curiosity when they select faces for restudy, independent of the prior related FOK experience.

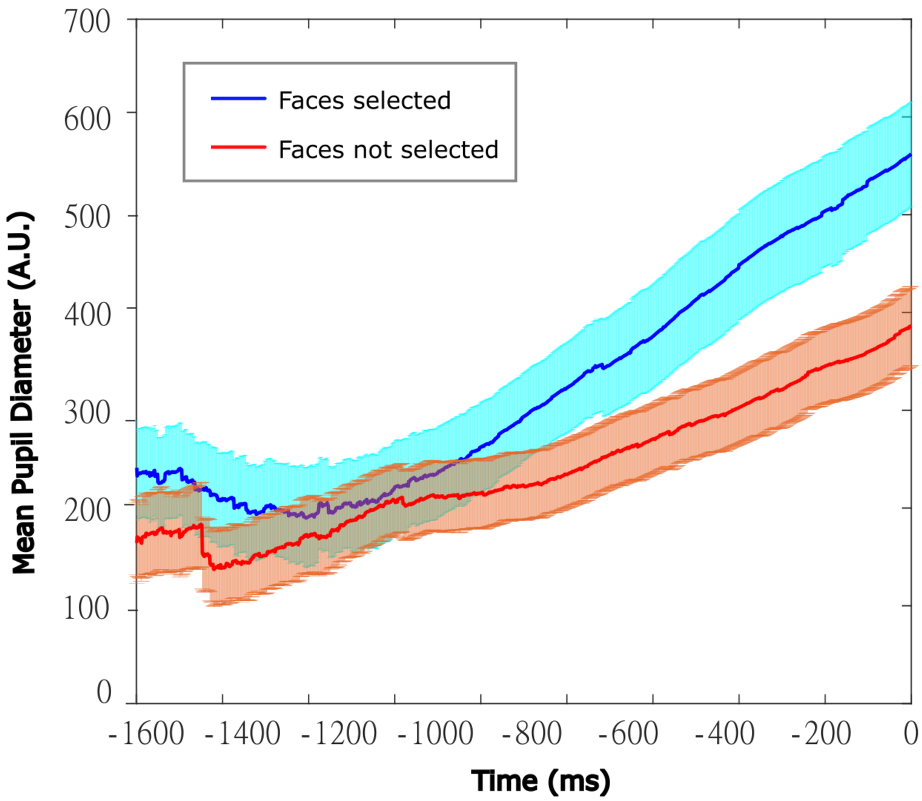

Figure 4. **Baseline corrected mean pupil diameter (arbitrary units) during Phase 3 of the experiment across all participants over time (ms) for faces selected for viewing of face-name pairs versus faces not selected (also during Phase 3 of the experiment). Standard error bars are represented in cyan around faces that were selected for restudy and in light red for faces not selected for restudy. Note that the figure is response locked, showing mean pupil dilation before and up to when participants made their information seeking selections.**

In a final analysis, we also explored if the pupil response preceding the selection of face-name pairs was linked to the degree of satisfaction experienced, using only those trials in which face-name pairs were selected for restudy. To examine this relationship, we computed the Spearman correlation between standardized mean pupillary response during Phase 3 and satisfaction ratings during the period preceding participants' selection. These results were not significant (*Mean rho* = 0.01, SD = 0.19), $t(38) = 0.28$, $p = .78$.

2.2.2.3 Summary of results for pupillary responses

The main findings of the pupillary analysis are summarized in Table 1. We conducted several two-way ANOVAs to explore the relationship between pupillary response and FOK ratings and later information seeking.

Table 1. ***Results of two-way ANOVA tests for Phase 2 – Recall Attempt & FOK Rating, and Phase 3 – Information Seeking & Satisfaction Rating.***

Dependent Variable	**Condition**	**Mean Pupil Diameter (SD)**	***F***	***P***	**Significant Effect**
Phase 2 Pupillary Response (Recall attempt)	**FOK rating 'high'** **FOK rating 'low'**	349.08 (291.33) 209.57 (227.18)	2.31	.14	
	Face selected **Face not selected**	328.88 (281.27) 209.57 (227.18)	1.80	.19	
	FOK rating: Face selection	N/A	0.13	.73	
Phase 2 Pupillary Response (FOK rating)	**FOK rating 'high'** **FOK rating 'low'**	32.53 (205.03) -55.96 (166.40)	17.41	<.001**	✓
	Face selected **Face not selected**	-11.30 (198.98) -42.94 (155.80)	2.06	.16	
	FOK rating: Face selection	N/A	0.95	.95	
Phase 3 Pupillary Response (Face selection during information seeking)	**FOK rating 'high'** **FOK rating 'low'**	231.03 (219.77) 196.48 (212.72)	0.01	.93	
	Face selected **Face not selected**	241.93 (265.43) 179.60 (192.00)	10.41	.0026**	✓
	FOK rating: Face selection	N/A	0.43	.52	

**$p < .01$; Note that negative mean pupil diameter values may result from subtraction of baseline activity.

Our results show that there is a significant relationship between FOK ratings and pupillary response during Phase 2, specifically when participants make their FOK ratings, with mean standardized pupil diameter being larger for faces rated higher in FOK. Additionally, we found a significant relationship between face-name selection and pupillary response during Phase 3, with mean standardized pupil diameter being larger prior to selection when participants viewed faces they would select for restudy.

Discussion

3 Discussion

3.1 Summary

The current study aimed to explore the role of autonomic arousal in curiosity induced by metacognitive experiences that accompany unsuccessful memory recall. The study also examined whether subsequent access to information that could not be recalled was experienced as rewarding and whether autonomic arousal played a role in the anticipation of this reward. These questions were explored using a FOK paradigm previously employed by Brooks et al. (2021), which was adapted to include a measure of autonomic arousal, the pupil dilation response, and satisfaction ratings as a measure of intrinsic reward.

Our results showed that participants were significantly more likely to choose to restudy the names of faces they previously rated higher in FOK and confirmed that FOK ratings predict subsequent information seeking behaviour, even when the familiarity of the faces employed was held constant. Additionally, participants found it more rewarding to view names in Phase 3 for faces they previously rater higher in FOK during Phase 2. Our pupillary results showed that mean pupillary response, and hence autonomic arousal, was greater for items rated high in FOK compared to items rated low in FOK. This difference was apparent specifically during the time period when participants made their FOK ratings and not before when participants made their recall attempts. Autonomic arousal during Phase 2 was not linked to information seeking behaviour in Phase 3, as there was no significant difference in mean pupil response in Phase 2 between faces later selected for restudy and faces not selected. These results suggest that autonomic arousal at the induction of curiosity is associated with metacognitive retrieval attempts during the FOK experiences, but not the earlier recall attempts, and was not linked to later information seeking. Additionally, our results showed that autonomic arousal played a role in the anticipation of the relief of the curiosity experience. Specifically, we found that pupils dilated significantly more during Phase 3 when participants viewed faces that they then selected for restudy of names versus faces they did not select for restudy. However, the pupil dilation response in Phase 3 was not linked to variations in the earlier FOK ratings, suggesting that pupil response when anticipating the relief of curiosity may not be directly related to the magnitude of the corresponding response when curiosity was induced.

3.2 Role of autonomic arousal in induction of curiosity

The results of the current study are consistent with previous findings showing that unsuccessful memory recall, namely FOK and TOT experiences, predicted to what extent participants subsequently seek information and hence sparked or induced curiosity (Brooks et al., 2021; Metcalfe et al., 2017). The current study also showed there is a relationship between autonomic arousal and FOK experiences associated with unsuccessful memory recall, with pupil dilation being greater when participants viewed faces they had rated higher in FOK. Brooks et al. (2021) previously established that familiarity of a face increases FOK ratings. Our results replicated these findings and confirmed that the observed relationship between autonomic arousal and FOK ratings was independent of the familiarity of the stimuli (i.e., faces). This was important given that our study included a familiarity manipulation, and there is evidence for an established relationship between familiarity and autonomic arousal, with pupils dilating more for previously seen compared to novel items (Gardner et al., 1974; Goldinger & Papesh, 2012; Heaver & Hutton, 2011; Naber et al., 2013; Papesh et al., 2012; Võ et al., 2008). Our findings suggest that the autonomic arousal response we observed in relation to metacognitive retrieval experiences is not simply a reflection of such old/new effects.

In a recent related study on the role of autonomic arousal in unsuccessful retrieval, Ryals et al.(2021) examined pupil dilation responses in TOT experiences tied to semantic memory, specifically unsuccessful word retrieval. They found that pupils dilated more in a TOT state compared to a non-TOT state. They interpreted their results as suggesting autonomic arousal and excitement are part of TOT experiences. The current study examined pupillary response in a metacognitive retrieval experience similar to the TOT state, the FOK experience, and showed that pupils dilate more during subjectively stronger FOK experiences (i.e., rated higher) compared to weaker FOK experiences (i.e., rated lower). Like Ryals et al., the findings of the current study suggest that autonomic arousal is associated with metacognitive retrieval, in this case, the FOK experience. Together, these findings suggest that autonomic arousal plays a role in different kinds of metacognitive retrieval experiences involving both semantic and episodic memory. Unlike the Ryals et al. study, the current study also examined the link between metacognitive retrieval experiences, autonomic arousal and curiosity. Notably, by showing that autonomic arousal is part of the FOK experience that induces curiosity, the current study suggests that autonomic arousal may be present when curiosity is induced.

Our results suggest that autonomic arousal was greater for faces that generated higher levels of curiosity, indicated by higher FOK ratings, at the time curiosity was induced during the FOK experience. This is an interesting parallel with the findings of Jepma et al. (2012), which also suggested a role for autonomic arousal during the induction of curiosity. In contrast to the current study, Jepma et al. used an fMRI paradigm to investigate the involvement of arousal and reward in curiosity induced by perceptual uncertainty using blurred images. They found that brain regions commonly associated with arousal were activated during the induction of curiosity and that reward circuitry was activated during the satisfaction of curiosity. Considering these findings in light of the current study suggests autonomic arousal is involved during the induction of different types of curiosity experiences.

When further examining the relationship between autonomic arousal and curiosity, our results showed that autonomic arousal at the time curiosity was induced during the FOK experiences did not predict later information seeking behaviour. Participants' metacognitive retrieval experience while making their FOK ratings was positively associated with autonomic arousal, but this arousal was not significantly related to later information seeking. This lack of relationship between autonomic arousal at the time curiosity was induced and later information seeking suggests that the aversiveness of the curiosity experience may not be what drives the later resolution of the experience via seeking out the missing information. Rather, the autonomic arousal that was present may instead reflect an aversive state that was related to almost recalling the missing information, and having a sense that it was available, while simultaneously not being able to recall the information. The aversiveness may reflect an unsettled or uncomfortable feeling associated with not being able to bring missing information to mind. These results support the concept of Berlyne (1954) that curiosity is an aversive state involving an arousal response but suggest that it may not be a key component of any persistent drive to resolve the aversive state through information seeking behaviour. This could be an indication that the drive to resolve the curiosity experience depends more on dopaminergic mechanisms rather than the noradrenergic mechanisms probed by the pupillary response. Dopamine has been implicated in learning new information that can happen after receiving a reward (Wise, 2004) and has been shown to play an important role in motivational drive. For instance, pharmacological manipulations that block dopamine have resulted in animals failing to learn to lever-press to obtain rewards like food and water (Wise, 1981).

3.3 Role of autonomic arousal in anticipation of relief of curiosity

In the current experiment, curiosity about unrecalled names induced by the FOK experience during Phase 2 was subsequently relieved or satisfied in Phase 3, when participants were shown the face-name pairs they selected for restudy. To understand the role of autonomic arousal in the anticipation of curiosity, we measured pupil dilation response during Phase 3. Our results showed that autonomic arousal was greater during the anticipation of the resolution of the curiosity experience. Namely, pupils dilated more when participants viewed faces they selected for restudy (i.e., when they would have been anticipating being shown the name) compared to when viewing faces they did not select. These results are consistent with the findings of previous researchers that demonstrated that pupils dilate more during the anticipation of the relief of curiosity. Specifically, Kang et al. (2009), as well as Brod and Breitwieser (2019), found that pupils dilated more when participants were about to view the answers to trivia questions they had rated higher in curiosity compared to items they had rated lower in curiosity. However, neither Kang et al. nor Brod and Breitwieser examined the relationship between curiosity and metacognitive retrieval experiences. As such, their findings do not provide information on the role that these types of retrieval experiences play in inducing curiosity and how that relates to autonomic arousal. Notably, the current study did examine the relationship between curiosity and metacognitive retrieval experiences associated with unsuccessful memory recall and showed that autonomic arousal was associated with the anticipation of the relief of curiosity induced by these experiences.

Previously, researchers have shown that pupils tend to dilate when individuals are anticipating receiving a reward (O'Doherty et al., 2003). Kang et al. (2009) interpreted anticipatory pupil dilation in their trivia memory experiment as an indication that curiosity is the anticipation of rewarding information and suggested that the associated noradrenergic arousal may be what enhances the learning of new information when curiosity is induced. Further, Marvin and Shohamy (2016) postulated that information in itself is rewarding and that curiosity is the motivation to obtain that reward. Indeed, the current study suggests that subsequent access to information that could not be recalled was experienced as rewarding, particularly for faces rated higher in curiosity. Participants were more satisfied when viewing names for faces they had previously rated higher in FOK. These findings suggest that the relief of curiosity was more rewarding for high curiosity items.

Overall, participants were more likely to seek out high curiosity information that could not be recalled (i.e., by selecting to view face-name pairs for faces they rated higher in FOK) and had increased autonomic arousal when anticipating the relief of curiosity for that information (i.e., when viewing faces they selected for restudy). Finally, when they obtained that information (i.e., being shown the selected face-name pair), the high curiosity information was perceived as more rewarding. Indirectly, the current study provides evidence that autonomic arousal associated with the anticipation of the relief of curiosity may reflect reward anticipation. Namely, autonomic arousal was greater when anticipating the relief of curiosity, and higher curiosity items were experienced as more rewarding. This suggests that the information seeking behaviour associated with the curiosity experience could be driven by the motivation to obtain a reward, with the reward being the information itself, consistent with the findings of Marvin and Shohamy (2016) about the reward value of information and how that drives the curiosity experience. An alternate interpretation that cannot be ruled out is that the observed autonomic arousal could be related to response selection of anticipation a surprise. This is an ambiguity that could be addressed through future study.

Brod and Breitwieser (2019) speculated that the anticipatory autonomic arousal response might be an indicator of the degree of curiosity elicited. In the current study, while autonomic arousal was greater when participants anticipated the relief of curiosity (i.e., when viewing faces they selected for restudy), anticipatory autonomic arousal was not linked to the level of curiosity that had been induced. There was no significant difference in pupil size at the time participants made their restudy selections during the information seeking phase of the experiment between FOK high and low conditions, the indicator of curiosity level in this paradigm. This suggests that autonomic arousal associated with anticipating the satisfaction of the curiosity experience may not be related to the level of curiosity previously induced by unsuccessful recall but may be more related to the anticipation of reward when this reward is imminent. Further, these findings suggest autonomic arousal plays a role in the induction of curiosity and anticipation of related reward that is associated with the satisfaction of curiosity but may not be involved in the maintenance of curiosity over time between induction and information seeking.

3.4 Limitations and future directions

The current study included some methodological limitations, which, if addressed, could provide further clarity and insight into the relationship between autonomic arousal and curiosity induced by unsuccessful memory recall. In the current study, pupil responses were measured over periods of time in which participants made self-paced decisions. The self-paced nature of these judgments made it difficult to compare the evolution of the pupillary response over time between participants. We addressed this issue in our analyses by comparing average pupillary responses over the duration of predefined experimental periods (e.g., from stimulus onset to FOK rating key press). For a more fine-grained examination of time courses, future studies could adapt the current study paradigm to include defined periods of time for the provision of memory judgments while autonomic arousal is being measured.

As discussed, there is ambiguity in the interpretation of the autonomic arousal response observed in Phase 3 of this study. While our results provide some support for the notion that anticipatory autonomic arousal when viewing previously unrecalled information could be linked to the rewarding nature of the information, some of our results conflict with this conclusion. We found no significant relationship between the size of the pupil responses preceding the selection of names for restudy and the degree of satisfaction expressed in subsequent ratings. This negative finding could suggest that anticipatory autonomic arousal may not be linked to the rewarding nature of having curiosity satisfied and could instead be linked to other factors that distinguish selection from non-selection trials, such as response preparation or general expectation or surprise effects. However, these results should be interpreted with caution given the limited number of trials available for comparison in this particular statistical analysis, which may be considered a methodological limitation of this study. Specifically, trials were only included in this particular analysis for faces that were selected for restudy, given those were the only trials where participants were asked to indicate their satisfaction following selection. Indirectly, however, our pupillary and behavioural results suggest that anticipatory autonomic arousal is linked to reward anticipation. Inasmuch as the selection of names for restudy was not constrained by any specific task goals but was encouraged to be based on intrinsic curiosity, it could be argued that the selection criterion was rooted in expected reward. The analyses supporting this conclusion, while providing only indirect evidence, included about twice the number of trials and hence provided more reliable results. Moreover, these results are consistent with the findings of several other studies suggesting that curiosity-driven information-seeking behaviour is closely tied to reward anticipation (FitzGibbon et al., 2020; Gruber et al., 2014; Kang et al., 2009; Marvin & Shohamy, 2016). This issue presents a potential area for future study, where an experimental setup could be developed in which there are more selection trials for analysis

While we did not measure recognition accuracy for the validation of FOK ratings in the current study, this is not viewed as a methodological limitation. Previous research has consistently shown that TOT and FOK ratings positively correlate with recognition accuracy in subsequent recognition memory tests (Brooks et al., 2021; KozLowski, 1977;

Schwartz, 2001). Furthermore, we verified the validity of the FOK ratings by confirming the sensitivity of the ratings to the included familiarity manipulation.

A potential area of future research is to further examine the aversive nature of the curiosity experience in the context of unsuccessful memory recall. Our results suggest that autonomic arousal was greater for faces that generated higher levels of curiosity at the time curiosity was induced during the FOK experience. Autonomic arousal present at the time of curiosity indication could potentially be associated with the aversiveness of the experience of not being able to recall an item, though the current experimental paradigm does not allow for this verification. Future research could adapt the study paradigm to include an aversiveness rating related to the FOK judgment or attempt to manipulate the aversiveness of the experience in combination with the monitoring of its impact on subsequent information-seeking behaviour. Additionally, the results of the current study show that autonomic arousal was greater for high curiosity items at the time curiosity was induced but that this autonomic arousal was not linked to subsequent information seeking. This suggests autonomic arousal is present when curiosity is induced but brings into question what role this arousal may play in this type of curiosity experience. Litman (2019) identifies two types of epistemic curiosity, interest and deprivation types. The deprivation type involves information seeking to resolve negative feelings like frustration associated with having missing pieces of information. The interest type involves satisfaction with exploring new ideas, wherein a drive to seek a reward may be the motivating factor. Interestingly, the results of the present research suggest that while the induction of curiosity involves autonomic arousal, the arousal does not directly drive subsequent information seeking behaviour, even when the curiosity experience is tied to seeking out missing pieces of information. Autonomic arousal linked to the noradrenergic system is not the only factor at play from induction to resolution of curiosity and may interact with other factors such as dopaminergic mechanisms tied to incentive salience. Such interactions have been described in other tasks. For instance, Varazanni et al. (2015) explored the involvement of both dopaminergic and noradrenergic systems in a decision-making task in monkeys. While they recorded the activity of dopaminergic and noradrenergic neurons, Varazanni et al. had monkeys perform a task involving squeezing a ball at varying levels of difficulty, paired with receiving varying levels of reward. This allowed the researchers to evaluate task effort, reward, and cost valuation in decision making and how that related to engagement of the neuronal systems. Based on their results, Varazanni concluded there are two systems involved in motivation, a “forward incentive system” and a “reactive difficulty system.” The forward incentive system involves activation of the dopaminergic system, which reflects expectations around the value of a decision, where the value is determined based on the anticipated reward as well as any costs associated with obtaining that reward. The reactivity difficulty system involves activation of the noradrenergic system and reflects mobilization of effort to meet the demands of the challenges associated with the selected task. The engagement of the dopaminergic forward incentive system may be what maintains curiosity over time in the current experimental paradigm.

3.5 Implications & conclusion

Given the established relationship between curiosity and memory (Brod & Breitwieser, 2019; Galli et al., 2018; Gruber et al., 2014; Kang et al., 2009; Marvin & Shohamy, 2016; Stare et al., 2018;), a better understanding of the mechanisms involved in curiosity could have implications for education and learning. Improved understanding of what induces intrinsic curiosity and what drives an individual to seek out information after curiosity is induced could, for instance, support educators in the development of learning models that motivate and enhance student learning. Given the emerging relationship between metacognitive experiences and curiosity, metacognitive experiences could be leveraged during unsuccessful recall for optimization of learning. Furthermore, curiosity is foundational in several fields related to knowledge seeking, like science and philosophy. Developing insight into what drives individuals to seek knowledge could have implications for improvements in these fields, as well as give knowledge seekers tools to inspire greater interest in their findings.

Overall, the present findings support the concept that autonomic arousal is part of the curiosity experience but suggest the motivation to seek out missing information when curiosity is induced by unsuccessful memory recall may not be driven by the autonomic arousal. Further, the current study showed that subsequent access to the information that could not be recalled is experienced as rewarding, particularly for items that induced greater curiosity. Autonomic arousal was found to play a role in the anticipation of the relief of curiosity, and the findings of this study suggest indirectly that anticipatory autonomic arousal reflects the anticipation of rewarding information.

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