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Uncovering the contents and dynamics of the stream of thought

Mildner, Judith Norbertine

Princeton, NJ : Princeton University

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Uncovering the contents and dynamics of the stream of thought

Judith Norbertine Mildner

a dissertation
presented to the faculty
of princeton university
in candidacy for the degree
of Doctor of Philosophy

recommended for acceptance
by the Department of
Psychology

Adviser: Diana I. Tamir

September 2022

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Abstract

The mind can access a vast landscape of thought. Our thoughts frequently wander away from the here and now to explore this landscape. In this dissertation, I examine the contents and dynamics of spontaneous thought to gain insight into its structure and function. In Chapter 1, I propose a theoretical framework that frames spontaneous thought as an unconstrained memory process. In this framework, semantic memory scaffolds episodic simulation to form the contents of thought. Our minds explore memory space in a clustered fashion, with thoughts focused within a particular topic until it is time to find new memories to explore. At that point, a drifting context shaped by one's current state helps determine which portion of memory space to explore next. In Chapter 2, I leverage predictions from this framework to test the function of spontaneous thought. I show that the dynamics of spontaneous thought prioritize episodic detail: the first thought in a new topic contains the most episodic detail, which decreases with each subsequent thought until it is time to find a new topic. Thoughts also prioritize goal-related content in a similar manner, although this content begins to increase in the thoughts immediately preceding a topic jump. These findings suggest that spontaneous thought helps optimize memory storage by replaying episodic details and aids in our ongoing goal pursuits by keeping current concerns in mind. In Chapters 3 and 4, I use sociality as a test case for the role of the external environment in shaping thought. Across different social contexts in the lab (Chapter 3) and in the real world (Chapter 4), I find that social spontaneous thought reflects the amount of social information in the environment, consistent with the hypothesis that spontaneous thought helps process incoming social information. Taken together, this work shows that spontaneous thought serves to both optimize memory and attend to current concerns. The external (social) environment and internal state can both affect the extent to which these functions are expressed in spontaneous thought.

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Chapter 1 has been previously published:
Mildner, J. N., & Tamir, D. I. (2019). Spontaneous Thought as an Unconstrained Memory Process. *Trends in Neurosciences, 42*(11), 763–777.

Chapter 3 has been previously published:
Mildner, J. N., & Tamir, D. I. (2021). The people around you are inside your head: Social context shapes spontaneous thought. *Journal of Experimental Psychology: General, 150*(11), 2375–2386.

Diana I. Tamir contributed to all chapters.

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Acknowledgments

This dissertation represents a seven-year journey full of ups and downs. I want to thank all the people who have steered me in the right direction and supported me along the way. I am so grateful to all of you.

First and foremost, I am grateful to my advisor, Diana Tamir, who has made this work possible in more ways than I can express. Diana took a chance on me seven years ago when she took me on as a visiting student, and she has not stopped taking chances on me since. From day one, Diana has encouraged me to think big and strive for rigorous, collaborative, and creative science in every part of the research process. She has been there to get me unstuck when things went wrong and to celebrate every success, large and small. Thank you for all your mentorship, incisive thoughts, trust, encouragement, and patience.

I also want to thank other faculty who have been generous with their time and feedback while serving on various committees, from my general examination committee to my reading and FPO committees: Susan Fiske, Nathaniel Daw, Ken Norman, Chandra Sripada, and Tom Griffiths. I am also grateful to my undergraduate advisor Nathan Spreng and my master's thesis supervisor Frank Zaal for helping me get here.

Next, none of this work would have been possible without the Princeton Social Neuroscience Lab community. Over the years, I have worked with some awesome humans who are also great scientists, including Abla Alaoui-Soce, Elyssa Barrick, Dominic Burkart, Aaron Kurosu Roek, Nathan Liang, Meghan Meyer, Jordan Rubin-McGregor, Mark Thornton, Lily Tsoi, and Miriam Weaverdyck. Thank you for all your support and generosity over the years. And, of course, a special thanks to my Princeton family: Zidong Zhao, who I grew up with in grad school and who has supported me through it all, and Kara Enz, whose superpower is neutralizing negativity. Thank you for all the adventures and family dinners, for making even lockdowns bearable, and, most of all, for being there for me.

Thank you to the grad student mental health survey team, including Mai Nguyen, Abigail Novick, Victoria Ritvo, and Sarah Wilterson, for the most therapeutic collaboration of my grad school career.

Thank you to Veronica 'Ronnie' Viar and Elena 'Rocky' Cuadros for the kind of friendship that doesn't fade with time and distance. Thank you to my best buddy Morrison 'MoMo' Mildner, for supporting all of my emotions, especially joy. Thank you to G Flipo and Kesha Sebert for the music that saw me through it all.

Finally, I would not be here without the unwavering support of my family, and I can-

not begin to thank them enough. I am grateful to the late Francis Mildner, Annebeth Spoorenberg-Mildner, and all my aunts, uncles, and cousins. Thank you to Max and Monique, who helped me get to Princeton in the first place. Thank you to the people who became family along the way; Alice, Myrthe, and Odile. But most of all, to the people who have been my navigators all along, Tineke Ausems, Vincent Mildner, Sebastiaan Mildner, bedankt voor alles!

1

Introduction: Spontaneous thought as an unconstrained memory process

In our minds, thoughts unfold continuously and freely. We can go from focusing on the world around us to noticing an emotion to thinking about something that happened in the past to imagining something that can never be, all in a moment's time. We spend almost half of our mental lives this way, drifting from unbidden imagery to future plans (Killingsworth & Gilbert, 2010). William James first described this ceaseless "stream of thought" over a century ago (James, 1890), and researchers today are still unraveling

the mysteries of how this stream flows through the landscape of thought (Callard et al., 2012; Christoff, 2012; Seli et al., 2018; Smallwood & Andrews-Hanna, 2013; Smallwood & Schooler, 2015). Scientists now use the term spontaneous thought to describe this kind of thinking, and they define it by its relatively unconstrained nature: spontaneous thought is all thought that unfolds unrestrictedly; it follows our mental whimsy whenever we are not fully focusing on explicit goals, external tasks, or salient stimuli.

The landscape of spontaneous thought includes mind wandering, daydreaming, creative thought, and even dreaming. How can researchers map out this vast territory? What determines what we think about from one moment to the next? In this dissertation, we approach these questions in two ways. First, we quantify the dynamics of spontaneous thought to test hypotheses about its function (Chapter 2). Then, we investigate the role of the environment in shaping the content of spontaneous thought (Chapters 3 & 4).

At the foundation of this work lies our theoretical framework of spontaneous thought. In this framework, we propose that spontaneous thought can be seen as an unconstrained memory process (Andreasen et al., 1995; Binder et al., 1999; Christoff et al., 2004; Mills et al., 2018; Rychlak, 1987; Smallwood & Schooler, 2015). Spontaneous thought draws on content from memory stores and arises from largely the same neural systems as memory search processes. Bridging the domains of spontaneous thought and memory, this chapter proposes a framework of spontaneous thought as a dynamic, associative, and state-dependent process built on semantic and episodic memory and guided by a drifting mental associative context and current state. In outlining this framework, we draw on existing computational models of memory search processes to identify how memory processes can give rise to spontaneous thought. This framework serves as the foundation for empirical

research on the dynamics and content of spontaneous thought in subsequent chapters.

Spontaneous thought as spontaneous memory replay

Episodic memory comprises much of the content of people's spontaneous thought. During periods of quiet rest, people spontaneously revisit recent experiences, a process known as offline memory replay (Buzsáki, 1989; Dewar et al., 2014; McClelland et al., 1995; Wamsley, 2019). Researchers estimate that approximately 60% of mind wandering occurrences are episodic in nature (Song & Wang, 2012).

However, while offline memory replay is a form of spontaneous thought, spontaneous thoughts are *not* merely direct recapitulations of past experiences. Instead, spontaneous thoughts often comprise counterfactual variations on past experiences and drive forward in time to visions of the future and imagined scenarios (Andrews-Hanna et al., 2013; Smallwood & Schooler, 2015). At least 50% of spontaneous thoughts are about the future and the past (Klinger & Cox, 1987; Smallwood & Schooler, 2015). Both types of thought – retrospective and prospective – draw upon episodic and semantic memory. According to the constructive episodic simulation hypothesis, people simulate future events or imaginative scenarios by flexibly recombining episodic details of past experiences (Schacter et al., 1998). Semantic memory contributes structure and meaning to these simulations (Irish & Piguet, 2013). This means that episodic simulation is the fodder for spontaneous thought: people recombine details of past episodes, scaffolded by semantic representations, to create novel episodic simulations of past or future scenarios (Andrews-Hanna et al., 2010; Christoff et al., 2016; Delamillieure et al., 2010; Fox et al., 2016; Hurlburt et al., 2015).

How do our memory systems support this type of unconstrained imagination? A key

neural hub in memory processes is the medial temporal lobe (MTL) subsystem of the default network, which includes the hippocampal formation, the parahippocampal cortex, and their cortical projections, including the retrosplenial cortex, ventral medial prefrontal cortex, and angular gyrus (Andrews-Hanna et al., 2010). The MTL, particularly the hippocampus, is well known for its role in semantic, declarative, episodic, and associative memory (Burgess et al., 2002; Kirwan & Stark, 2004; Moscovitch et al., 2016; Squire et al., 2004; Tulving & Markowitsch, 1998). It allows us to remember what we experienced and where we experienced it (Cansino et al., 2002; Davachi, 2006; Davachi et al., 2003; Jenkins & Ranganath, 2010) by linking experiences to their temporal and spatial contexts (Eichenbaum, 2000, 2004). Regions such as the angular gyrus (Seghier, 2012) and parahippocampal cortex (Aminoff et al., 2013) offer the structure required to construct mental simulations (Andrews-Hanna et al., 2010; Buckner & Carroll, 2007) by integrating experiences into more abstract, conceptual knowledge (Seghier, 2012) and tracking contextual information during episodic simulation (Ramanan et al., 2018).

The hippocampus is also the neurobiological source of spontaneous, "offline" memory replay. Rodent studies tell us that during periods of rest after a task, the hippocampus replays its recent real-life experiences. For instance, after a rodent runs down a track or explores a maze, neurons in the hippocampus that encode spatial locations will spontaneously reactivate during rest, replaying the rodent's experience with the newly learned trajectory (Ólafsdóttir et al., 2018). Humans likewise spontaneously replay recent experiences at rest (Ben-Yakov et al., 2013; Momennejad et al., 2018; Tambini et al., 2010; Wamsley, 2019). This replay in humans again has its origins in MTL activity (Ben-Yakov et al., 2013; Fox et al., 2016; Meyer et al., 2018; Selimbeyoglu & Parvizi, 2010; Tambini et al., 2010). But

spontaneous hippocampal replay does more than recapitulate "online" hippocampal activity from the original, real-life episode. Instead of just replaying the trajectories of recent experiences, the hippocampus generates novel reconfigurations of these experiences in the same environment (Gupta et al., 2010). Replayed trajectories can follow a seemingly random pattern through the explored environment and often do not correspond to the rodent's actual movement pattern (Stella et al., 2019).

During periods of rest, when people are most likely to experience spontaneous thought, the brain traces a seemingly random trajectory through its recent experiences. This random trajectory arises from an episodic memory retrieval mechanism known as pattern completion (Marr, 1971): partial activation of one memory representation triggers activation of the entire pattern. For example, seeing someone eat ice cream might activate a memory of going out for ice cream on a hot summer's day; summer might trigger a memory of swimming; the color blue might remind you of the cover of a book you read recently, and so on. A series of cascading pattern completions can activate one memory after another, creating both novel patterns in the hippocampus and novel patterns of distributed neocortical activity (Mills et al., 2018). The result is a type of "wandering" neural activity that can help explain the "wandering" nature of much spontaneous thought.

Spontaneous activity in the MTL network generates these variable neural patterns. In turn, the interaction between regions in the brain's default network (Andreasen et al., 1995; Andrews-Hanna et al., 2010; Andrews-Hanna, 2012; Binder et al., 1999; Buckner et al., 2008; Christoff et al., 2009, 2016; Ellamil et al., 2016; Fox et al., 2015; Mason et al., 2007; Spreng & Grady, 2009; Van Calster et al., 2016; Wang et al., 2009) integrates these patterns into spontaneous thought: The MTL couples with the core subsystem of the default net-

work, which consists of the medial prefrontal cortex and posterior cingulate cortex, to inject its highly variable content into the stream of thought (Christoff et al., 2016; Mills et al., 2018). This means that the MTL is involved in the associative, imaginative, and creative thinking that occurs during spontaneous thought (Beaty et al., 2018; Buckner & Carroll, 2007; Schacter & Addis, 2009; Schacter et al., 2007, 2012), partly because this kind of thinking, like memory replay, draws on past episodic experiences. These periods of spontaneous thought during unoccupied wake time, like periods of dreaming, support optimal learning and memory consolidation (Carr et al., 2011; Dewar et al., 2014, 2007), which make it possible for people to strategically review and generalize from their experiences.

Features of spontaneous thought

We can leverage the parallels between memory and spontaneous thought to build a framework of spontaneous thought. Such a framework needs to account for three key features of spontaneous thought: its dynamism, its associativeness, and its state dependence.

Dynamic. Spontaneous thought is highly dynamic: thoughts move from one topic to the next continuously (Christoff et al., 2016), at an estimated rate of about 4.3 thought transitions per minute (Tseng & Poppenk, 2019). The speed of this movement varies (Pronin & Jacobs, 2008), but whether it unfolds slowly or quickly, thought is always in motion. William James (James, 1890) described this dynamism: "Like a bird's life, [the stream of thought] seems to be made of an alternation of flights and perchings" (p. 243). The "perchings" represent substantive, concrete content that can be held in mind for longer. The locations where the mind may perch cover a vast area within the landscape of thought (Finnbogadóttir & Berntsen, 2013). Perches can also vary widely in modality: they can be images,

words, auditory experiences, emotions, or physical sensations (Buckner & Carroll, 2007; Delamillieure et al., 2010; Gorgolewski et al., 2014; Hassabis et al., 2007; Hurlburt et al., 2015; Schacter et al., 2012; Suddendorf & Corballis, 2007; Szpunar, 2010; Taylor et al., 1998; Wheeler et al., 1997). The "flights" are dynamic transitions between these states; they are rapid and transitory, and each flight may cover a long distance within the mental landscape.

Associative. Flights from one thought to the next may be highly variable, but they are not random. Instead, thoughts are highly associative (Bar et al., 2007): they are linked by preexisting associations between topics. This associative feature of thought is a staple of many classic philosophical accounts of thought and reasoning (Rychlak, 1987), as well as explanations for creative thought (Mednick, 1962)

State-dependent. The flights and perches of thought are also affected by features or cues provided by one's current state. While spontaneous thought is free from strong constraints by definition, it can still be subject to weak constraints. For instance, thought can be shaped by *external* factors, such as one's location and the stimuli in it, and *internal* factors, such as one's mood or ongoing goals. Even without strong attentional coupling to the immediate environment, internal and external stimuli can still be starting points for thought. The brain can integrate these stimuli into spontaneous thoughts as they form (Northoff, 2018). Internal states (e.g., negative affect) can modulate the direction in which thoughts proceed (e.g., toward events in the past; (Poerio et al., 2013)), and personal goals or motivations, known as current concerns, can modulate the likelihood that thoughts circle back to a particular topic (Klinger, 2013). In other words, thoughts are shaped not just

by preceding thoughts but also by the current state of the person doing the thinking and the world around them.

Parallel dynamics in memory and spontaneous thought

In sum, spontaneous thought is dynamic, associative, and state-dependent. Memory search and recall processes share these same three features. For instance, successful retrieval of a relevant memory relies on a highly dynamic memory search process that moves quickly through candidate memories (Cavanagh, 1972; Reiser et al., 1986; Williams & Hollan, 1981). This memory search process is also highly associative: existing associations between different memories determine what is recalled next (Bousfield, 1953; Howard & Kahana, 2002; Raaijmakers & Shiffrin, 1981; Romney et al., 1993). And like spontaneous thought, episodic memory retrieval is sensitive to the current state: mood, culture, and local external cues all affect recall (Rholes et al., 1987; Tulving & Schacter, 1990; Wang & Ross, 2005). These shared features offer further evidence for the considerable overlap between spontaneous thought and the more constrained forms of thought involved in memory search.

A framework of spontaneous thought

Memory and spontaneous thought comprise similar content and arise from similar neural substrates (Christoff et al., 2016, 2004; Fox et al., 2016; Mills et al., 2018; Singer, 1974; Wamsley, 2018; Wang et al., 2009). Here, we study the function and content of spontaneous thought by attending to the features it shares with memory. Memory researchers have an established practice of developing formal models to explain the dynamics of memory search processes (Bower, 2000). Computer scientists have successfully used episodic

and semantic memory to develop artificial intelligence that mimics the dynamics of day-dreaming (Mueller, 1990) and creative ideation (Marupaka et al., 2012). To the extent that spontaneous thought can be understood in the same way as episodic and semantic memory processes, we should be able to apply models from the cognitive psychology of memory to better understand how spontaneous thought unfolds; to the extent that models of memory fail to capture spontaneous thought, we can adapt the model and, in doing so, hone our understanding of spontaneous thought. Here we offer a framework for understanding the flights and perches of spontaneous thought, which we use as a foundation for the empirical work in Chapters 2-4 (Figure 1.1).

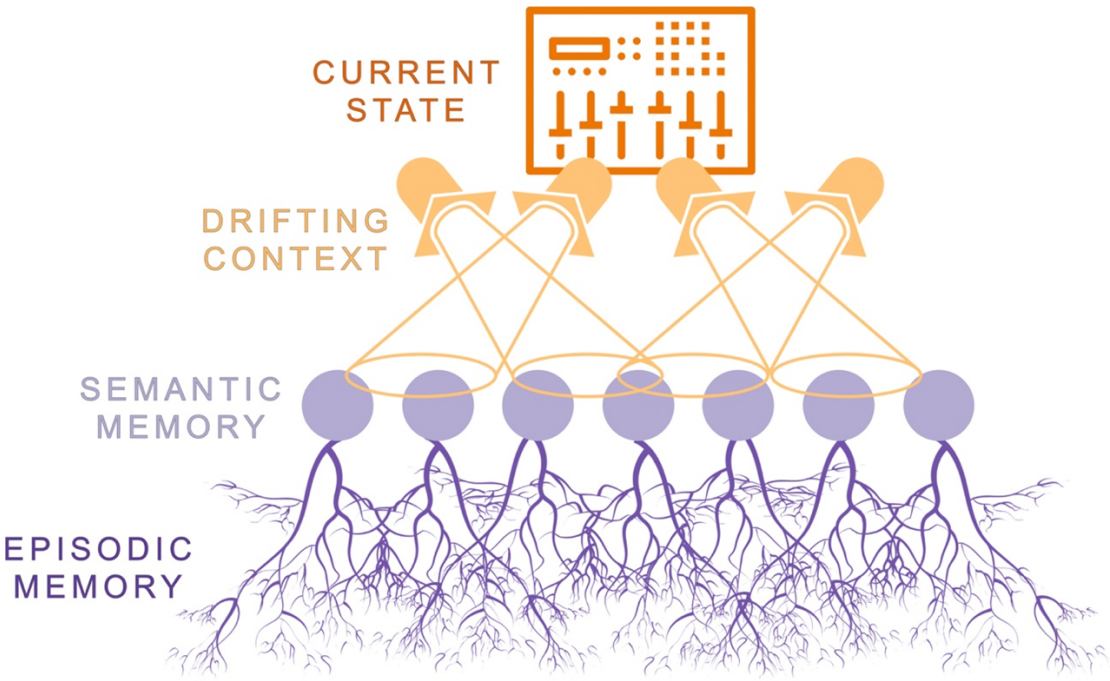

Figure 1.1: A framework of spontaneous thought. At the lowest level, thought consists of episodic memory content. Episodic memory is scaffolded by semantic memory to form simulations. The next semantic topic of simulation is determined by a combination of multiple drifting context representations, each implementing a different kind of association. At the top level, current state variables alter the strength of each different context representation.

The dynamics and function of spontaneous thought

At the base of this framework lies the content that spontaneous thoughts and simulations draw on episodic memory (Christoff et al., 2016; Mills et al., 2018). These episodic seeds, generated by the MTL, provide the characteristic highly variable content of spontaneous thought. Semantic memory scaffolds the construction of novel episodic simulations (Irish et al., 2012a,b; Irish & Piguet, 2013). Semantic memory stores our abstract knowledge about the world (Tulving, 1972) and our past (Renoult et al., 2012), which is necessary to support abstract reasoning, counterfactual thought, and imagination (Abraham & Bubic, 2015). During spontaneous thought, semantic memory provides structure for episodic memory to fill in the experiential details (Irish & Piguet, 2013). Indeed, several clinical disorders of spontaneous thought can be traced to deficits in episodic memory or its semantic scaffolding. Although typically considered distinct types of memory, semantic and episodic memory are tightly linked and sometimes hard to distinguish (Renoult et al., 2012). Our framework attempts to capture their continuous dynamic interplay.

Foraging models of semantic search

How can a stream of thought arise from the structure of these two types of memory content? To answer this question, we turn to computational memory models. A common task used to study the dynamics of memory search is the semantic fluency task, where participants name as many items as possible from a target category (e.g. animals). Participants' pattern of responses in this task is a window into the organization of semantic memory's content and the process the mind uses to explore that content. For instance, in a semantic fluency task with the category "animals," people may first name pets (e.g., cat, dog, fish),

then aquatic animals (e.g., shark, whale, dolphin), then farm animals (e.g., cow, sheep, pig), and so on. This process shares the dynamics and associativeness of spontaneous thought. Therefore, models of semantic fluency can illuminate the path of spontaneous thought through the landscape of memory.

Models of spatial foraging have been highly successful at explaining participant responses during semantic fluency tasks. These models can explain why participants retrieve semantically related items in clusters and how and when people switch from one cluster to another (Hills et al., 2012a). In spatial foraging, animals search for resources that occur in patches (e.g., berries on bushes) within an environment with many such patches (e.g., distributed bushes). Animals continue to search in a local patch until it becomes too difficult to find what they are looking for there. At that point, they leave the current patch to find a new, unpicked one. The optimal time to switch to a new patch is when the rate of collecting new items in the current patch decreases to the same rate as the long-term average intake over all patches. This spatial foraging model can be applied to semantic space instead of physical space to model semantic fluency tasks: We store conceptually related items in semantic clusters just as berries are stored on bushes. Participants who perform better at the semantic fluency task tend to switch to a new "patch" closer to the computationally derived optimal time.

Ultimately, this model explains semantic search in a way that resembles the "flights and perches" of spontaneous thought. Perches are the items within the clusters or patches distributed in semantic space, and flights are the processes the mind uses to traverse this space. The foraging model captures many of the key features of spontaneous thought.

We can borrow from the foraging model to describe how people traverse memory stores to generate dynamic, associative spontaneous thoughts. The primary difference between a model of memory search and a model of spontaneous thought is that the former operates over an explicit goal, whereas the goal of spontaneous thought is, as yet unknown. These memory models describe a process designed to forage as many resources from semantic memory as possible. Resources are sources of "value" that motivate the memory search to unfold as it does. What are the resources that guide the spontaneous thought stream? We suggest that, in applying the principles of goal-directed memory search to goal-free mental wanderings, we can begin to answer an outstanding question about spontaneous thought: what goal is spontaneous thought optimized to achieve?

In Chapter 2, we apply insights from the foraging model to spontaneous thought to investigate the function of spontaneous thought. To do so, we first quantify the dynamics of spontaneous thought using think-aloud data. Then, we test two of the leading hypotheses about the functions of spontaneous thought: First, we test the hypothesis that spontaneous thought improves memory efficiency (Mills et al., 2018; Wamsley, 2022). This hypothesis stems from the literature on memory replay and consolidation during rest (Ben-Yakov et al., 2013; Craig et al., 2015; Meyer et al., 2018; Tambini & Davachi, 2019; Wamsley, 2022). Under this hypothesis, the dynamics of spontaneous thought should resemble the pseudo-random memory replays that optimize memory storage and facilitate learning (Mills et al., 2018) such that spontaneous thought prioritizes detailed, vivid simulations. Next, we test the hypothesis that spontaneous thought helps us achieve our goals (Klinger, 2013; Klinger et al., 2018). This hypothesis stems from prior work showing that spontaneous thought

often centers on ongoing goal pursuits (Baird et al., 2011; Klinger & Cox, 1987; Klinger, 2013), possibly to ensure that the mind is prepared to act on goals when the opportunity arises. Under this hypothesis, spontaneous thought should prioritize goal-relevant content.

To arbitrate between these two possible functions of spontaneous thought, we will test predictions based on two versions of the foraging model. In one version, the patch switching threshold prioritizes goal-relevant information: thoughts will move on to a new patch when thoughts within the current patch stray too far from goal-related information. The second version will have a patch-switching threshold that prioritizes optimal memory replay: thought will move on to a new patch when the level of episodic memory detail related to the current patch becomes too low.

The foraging model can provide a window into the low-level dynamics of spontaneous thought. However, they do not explain how people select which region of semantic and episodic space to search within the vast scope of possible spontaneous thoughts. That is, there are more constraints on thought paths than merely the semantic structure over which foraging models are optimized to search. Therefore, we next add two layers to our framework to fully explain the trajectory of thought through semantic space.

The content of spontaneous thought

In addition to the layers representing spontaneous thought's episodic and semantic content, our framework incorporates two superordinate layers: drifting mental context and the current state. Both of these layers help determine what area of semantic space to explore by shaping the strength of the association between thoughts. During spontaneous thought, our minds can traverse all associations acquired over a lifetime. The semantic search models

introduced above approximate such an associative structure based on the static properties of natural language use. However, spontaneous thought can explore such a vast semantic space that this approximation is insufficient to fully determine the path of thought. Our framework incorporates a layer that accounts for multiple types of associations between concepts, including not only semantics but also time, space, social structure, emotions, etc. Importantly, this context layer dynamically updates based on the content of the current thought. In addition, we know that spontaneous thought is shaped by one's current state, as described above. Our framework incorporates these factors as a fourth layer to account for the state-dependence of the content selection process.

How can we characterize the drifting contexts and states that select which portion of memory space to explore? To answer this question, we once again turn to computational memory models. Memory search during free recall is an apt process to focus on. During free recall tasks, participants study a list of words and then recall them later. Retrieval in this task is unstructured, yet there are consistent patterns in the order in which participants retrieve items. For instance, responses often reflect the order in which the items were presented during the learning phase. Like spontaneous thought, free recall involves traversing concepts based on the associations between them.

Our minds can rely on many different types of associations during free recall, such as semantic associations, temporal context (when the concept was learned), and source context (where the concept was learned). Concepts will activate multiple types of associations at a time, which together define the drifting mental context at that moment in recall (Polyn et al., 2009). Spontaneous thought similarly relies on a drifting mental context that incorporates various types of associations. Compared to free recall, spontaneous thought covers

a much larger space of target items, contexts, and associations among them. We propose that the weights placed on each association in the drifting mental context vary according to the mind's current state. The current state encompasses both the external environment, including local stimuli, and the internal mental state, including affect and current concerns.

In our framework, the current state is a superordinate layer that modulates the weights assigned to different context associations. To test this framework component, we can manipulate the state before and during a thought sample to affect the currently salient contextual associations that determine the next topic of thought. For example, social associations might become more important in a highly social environment (Mildner & Tamir, 2021). In Chapters 3 and 4, we use the social environment as a test case for the effect of the current state on the content of spontaneous thought.

Spontaneous thoughts overwhelmingly feature other people. Under our framework of spontaneous thought, this could mean that the social world is a factor of our current state that adjusts the drifting mental context to prioritize social information. There are two ways in which the social environment may shape spontaneous social thought. First, thought may be social because people are embedded in a social world. If spontaneous thought helps optimize memory efficiency (Chapter 2), then we expect that the amount of social content in spontaneous thought reflects the amount of social information in the environment and increases after social interaction when there is new social information to process. Alternatively, thought may be social because people have an innate need for social connection. If spontaneous thought prioritizes current concerns, we expect that the amount of social content in spontaneous thought reflects social needs and increases in social isolation when there is insufficient social contact.

In Chapter 3, we test these two hypotheses in a series of controlled experiments where we systematically vary the amount of social interaction from complete social isolation to face-to-face social interaction. In Chapter 4, we test these hypotheses again using real-world data from people who experienced dramatic changes in their social environment.

Summary

When all elements are combined, they yield a framework with four components: episodic memory, semantic memory, drifting context associations, and current state (Figure 1.1). The dynamics of thought are generated by a random walk over episodic memories scaffolded by semantic space. A foraging mechanism determines when to move on to a new portion of semantic space. At that time, a drifting mental context determines which area to search and where thought goes next. The different kinds of associations that make up this mental context are not all weighted equally: instead, the weights can shift based on the current state.

Together, these four components provide a framework for spontaneous thought. This framework leverages cognitive psychology's understanding of memory to account for the key features of spontaneous thought: its dynamism, its associativeness, and its state-dependence.

In this dissertation, we use this framework to investigate what determines the dynamics and content of spontaneous thought. In Chapter 2, we examine the dynamics of spontaneous thought through episodic and semantic memory space. We then test hypotheses about what these dynamics are optimized to achieve. In other words, what is the function of spontaneous thought? Chapters 3 and 4 test how the current state affects topic selection

in spontaneous thought using the social environment as a test case. Does the content of thought reflect our external social environment? Together, these chapters provide some empirical evidence for our framework of spontaneous thought and demonstrate how it can be applied to gain new insights into the structure, function, and implications of spontaneous thought.

2

What is the function of spontaneous thought?

We spend most of our mental lives engaging in spontaneous thought, like unbidden imagery, mind wandering, and dreaming. Why do we spend such large amounts of cognitive resources and time on spontaneous thought? Spontaneous thought, particularly mind wandering, is sometimes regarded as a failure of attention or executive function. However, spontaneous thought may serve an adaptive purpose that merits the vast amounts of cognitive resources and time we spend on these thoughts. We aim to investigate

the function of spontaneous thought by quantifying the contents and dynamics of spontaneous thought.

Possible functions of spontaneous thought

There are two leading hypotheses about the function of spontaneous thought. First, spontaneous thought may center on memory replay, optimized to facilitate encoding of new memories and semantic abstraction (Christoff et al., 2011; Dewar et al., 2014; Meyer et al., 2018; Mills et al., 2018; Tambini & Davachi, 2019; Wamsley, 2019). Second, spontaneous thought may center on ongoing goal pursuits, or current concerns, to process goal-relevant information from the environment and ensure that we are always prepared to act according to current concerns (Klinger, 2013, 1971; Spunt et al., 2015). We discuss each of these possibilities in turn.

Memory optimization hypothesis

Spontaneous thought may be a form of memory replay optimized to improve memory efficiency. During memory replay, new experiences are consolidated (Born & Wilhelm, 2012; Ellenbogen et al., 2007; Fachechi et al., 2019; Tambini et al., 2010; Wamsley, 2019). There is evidence that periods of rest after learning new information can enhance memory for this information (Dewar et al., 2014; Tambini & Davachi, 2019; Wamsley, 2022). Memory-related neural activity during the rest period predicts the extent to which rest facilitates memory consolidation, suggesting that this effect results from memory replay during rest (Ben-Yakov & Dudai, 2011; Craig et al., 2015; Meyer et al., 2018; Tambini et al., 2010; Tambini & Davachi, 2013; Wamsley, 2019; Wamsley & Summer, 2020).

The neural dynamics of spontaneous thought appear to be well-suited to enhance episodic and semantic memory (Mills et al., 2018). Episodic events are encoded in specific patterns in the medial temporal lobe. Overlapping patterns must be sufficiently disentangled to avoid competition between similar memories during retrieval (Hulbert & Norman, 2015). Activating memory traces out of their original order can help optimize episodic memory storage by decorrelating individual episodic events that occurred close together in time. During spontaneous thought, memory traces are reactivated in novel and variable sequences. These novel sequences can help decorrelate episodic memories, thus optimizing episodic memory storage (Mills et al., 2018).

At the same time, reinstating episodic memories multiple times in different contexts helps optimize semantic memory (Mills et al., 2018). We learn semantic information by generalizing across many episodic experiences. This learning process is most efficient when many examples are presented in a somewhat random order to minimize interference from irrelevant shared features, such as time (Sripada, 2016). Much of the content of spontaneous thought consists of exactly this type of varied episodic simulations (Mills et al., 2018), random replays, and recombinations of recent experiences.

Taken together, these ideas suggest that the function of spontaneous thought may be the optimization of episodic memory storage and semantic abstraction. This is supported by the fact that episodic simulation is a significant component of the content of spontaneous thought. In an experience sampling study, episodic thought made up 60% of the content of thought (Song & Wang, 2012). This content can reflect the past but often takes the form of future simulation (Baird et al., 2011; Berntsen, 2021; D'Argembeau et al., 2011; Smallwood & Andrews-Hanna, 2013; Smallwood & Schooler, 2015; Stawarczyk et al., 2011,

2013). Additionally, spontaneous thought tends to center on psychologically proximal content, such as recent or near future experiences (Andrews-Hanna et al., 2013; D'Argembeau et al., 2011; D'Argembeau & Van der Linden, 2004; Spronken et al., 2016). Since proximal episodic details are easier to recall than distal ones (Addis & Schacter, 2008; Johnson et al., 1988; Trope & Liberman, 2010), this is consistent with the idea that thought prioritizes episodic detail.

Current concerns hypothesis

Much of the thematic content of spontaneous thought comprises ongoing goal pursuits or current concerns (Klinger, 2013; Klinger et al., 2018). Stimuli associated with people's personal goals are readily adopted into dreams and waking spontaneous thoughts (Klinger & Cox, 1987), and people report thinking about goal-relevant content often (Klinger et al., 2018). In fact, a prevalent theme in spontaneous thought is planning for the future (Baird et al., 2011). This emphasis on current concerns during spontaneous thought can be adaptive in multiple ways. For example, it can serve as an ongoing reminder of overarching goals when we cannot directly engage with them, help us plan future goal pursuits, and help develop creative solutions for goal-related problems (Klinger et al., 2018).

Thoughts that address a current concern may be more "valuable" than wholly undirected thoughts (Klinger et al., 2018; Westgate et al., 2017). Under this hypothesis, spontaneous thought may be a valuable tool to ensure that the mind is primed and prepared to act on current concerns when the opportunity arises (Baird et al., 2011; Meyer, 2019; Spunt et al., 2015). For instance, in one study, neural activity during rest in brain regions associated with thinking about oneself facilitated subsequent performance on a self-referential

processing task (Meyer & Lieberman, 2018). As such, another possible function of spontaneous thought is to facilitate goal pursuits by keeping our minds primed to attend to and act on goal-relevant information. It is important to note that the current concerns and memory optimization hypotheses are not mutually exclusive. Consolidating new information can facilitate effective future behavior. For instance, researchers found that a period of rest after listening to an emotional disclosure not only facilitated memory consolidation for the disclosure but also predicted social support towards the speaker the next day (Collier & Meyer, 2020).

Quantifying the function of spontaneous thought

In our framework of spontaneous thought (Chapter 1), thought consists of episodic simulations scaffolded by semantic memory. Under the framework, the dynamics of spontaneous thought are similar to the dynamics of recall in semantic fluency tasks: We expect that spontaneous thought has a clustered structure, with thoughts exploring a particular topic until it is time to jump to a new topic. This clustered structure has recently been identified empirically in spontaneous thought (Sripada & Taxali, 2020). Quantifying the dynamics of spontaneous thought allows us to track when these jumps occur, offering insight into *why* they occur. In doing so, we can elucidate why we spend so much time and energy engaging in spontaneous thought. Since the dynamics of spontaneous thought are similar to the dynamics of semantic fluency, we can apply techniques used in analyzing semantic fluency tasks to quantify the dynamics of spontaneous thought.

Optimal foraging models

In semantic fluency tasks, participants tend to recall clusters of related items together. For example, when asked to name as many animals as possible, people may first list different kinds of pets, then farm animals, then aquatic animals, and so on. This process has been modeled using a spatial foraging model. Under this model, items form clusters in semantic space, analogous to patches in spatial foraging. When it becomes too difficult to find new items in the current patch, it's time to find a new patch to explore (Hills et al., 2012b). To optimize the efficiency of foraging, the best time to switch to a new patch is when the rate of retrieval within the current patch drops to the overall average retrieval rate. This threshold is highly informative, as it exposes a computational parameter that represents the efficiency of foraging in terms of a concrete goal. In spatial foraging and semantic fluency, the goal is to maximize the number of items retrieved over time, so the threshold represents the rate of retrieval. By changing what the threshold represents, we can use it to model what optimization looks like for other kinds of goals. Specifically, we will use it to test the memory optimization and current concerns hypotheses.

Testing the function of spontaneous thought

We can use the thresholding in this model to gain insight into the function of spontaneous thought. If spontaneous thought is designed to optimize memory storage and facilitate learning, its trajectory will leave traces of this memory function throughout its content and dynamics. Repetition of episodic detail helps optimize episodic memory and facilitates extraction of semantic knowledge (Mills et al., 2018). We therefore expect spontaneous thought to prioritize detailed and vivid simulations. Applying this to the optimal foraging

theory, we predict that in spontaneous thought, topic switches will occur when the rate at which episodic details are produced decreases below the average rate. This would produce a pattern of thought where the first thought within a new topic contains a lot of episodic detail, and each subsequent thought decreases in episodic detail until the next topic switch.

If spontaneous thought is designed to keep our minds focused on current concerns, we would similarly see this reflected in its content and dynamics. In this case, we expect spontaneous thought to prioritize all content that is in some way relevant to ongoing goal pursuits. In terms of foraging, we predict that topic switches occur when the amount of goal-relevance of thought in the current topic drops below the overall average goal-relevance of thought. This would produce a pattern where the first thought in a new topic is highly goal-relevant, and each subsequent thought decreases in goal-relevance until the next topic switch. The current study uses think-aloud data to examine the function of spontaneous thought. We first use natural language processing to detect the boundaries between thoughts and topics in thought. We then test the memory optimization hypothesis by examining the trajectory of thought in terms of episodic details and the current concerns hypothesis by examining the trajectory in terms of goal relevance.

Methods

Participants

We collected 3,332 responses from 1,679 participants (mean age = 39.8, range [19.0 – 79.0], 15.9% Asian/Asian American, 14.1% Black, 7.0% Latinx, 1.0% Native American, 65.7% White, 56.6% women, 1.3% genderqueer/non-binary/other) in three separate data collections between April 2020 and May 2021. Informed consent was obtained from all par-

ticipants in accordance with the Princeton University Institutional Review Board. This study was conducted as part of a larger data collection effort. Participants completed up to 9 measures not included in this study, including surveys on the social environment and (social) well-being. Findings from other measures in the survey are available elsewhere (see also Chapter 4).

Data collection 1. In the first data collection, participants were recruited through email lists at Princeton University and on social media. These participants volunteered their time and could participate as many times as they wanted, at least five days apart (n = 371; responses = 532).

Data collection 2. The second data collection occurred through the Center for Decision Research at the University of Chicago Booth School of Business. Participants received $4 each time they participated and were invited to participate twice, in April 2020 and May 2020 (n = 285; responses = 488).

Data collection 3. Participants in the final data collection were recruited through Prolific Academic (www.prolific.co) and received $4 for their participation. The first wave was collected in May 2020, and the same participants were invited again in June 2020 and April 2021 (n = 1023; total responses = 2311). In wave 2, 831 participants returned; in wave 3, 477 participants returned. These participants were a representative sample matched to U.S. census values for sex, age, and ethnicity.

Totals & Exclusions. In every data collection, participants completed the study online on their own devices (mobile, tablet, or computer). For this study, we only included

participants who spoke or wrote between 25 and 500 words in the Think Aloud task (see below). After exclusions, 1,637 participants provided 3,208 responses (Princeton: n = 355, responses = 506; Chicago: n = 276, responses = 463; Prolific: n = 1,006, responses = 2,239).

Measuring spontaneous thought

To measure the dynamics of spontaneous thought, participants completed a Think Aloud task, as the first task presented during a more extensive data collection effort (see Chapter 4). During Think Aloud tasks, participants are asked to narrate their stream of thought in real-time. While think-aloud protocols were initially used to study thought processes during tasks (Ericsson & Simon, 1984), these methods can also be used without any external task to study spontaneous thought (Raffaelli et al., 2021; Sripada & Taxali, 2020).

In this study, participants were first told that they would record a short audio clip and received instructions on testing their microphones. After successful testing, participants were given the following task instructions:

> For 2 minutes, please report whatever you can on your stream of thought. Your report may include (but is not limited to) descriptions of: images, conversations, thoughts, sensations, feelings, memories of past experiences, thought or images of future experiences. Simply say whatever is going through your mind from moment to moment. Report your thoughts and feelings as they come to you. Try to talk continuously during the entire time. Don't worry about grammar or complete sentences. If your thoughts or feelings recur over and over, simply say them over and over. Remember that we are interested in

> your saying any and all thoughts and feelings that come to you no matter how silly or personal you think they may be.

Next, participants saw a screen with a reminder to report their thoughts and feelings as they came to them and a record button. Upon pressing record, a progress bar appeared to indicate how much time was left in the task. The recording was stopped automatically after 2 minutes.

Participants could opt out of audio recording and type on their keyboards instead. Participants who opted out of audio recording saw a screen with similar instructions and a textbox in which they could type their thoughts. Instructions asked participants to type their thoughts and feelings as they came to them. Participants were also informed that only the latest portion of their response would be visible to them to allow them to focus on their current thoughts. The textbox only showed the most recent 100 characters. After the two minutes were up, a "next" button became active, and the participants could leave the task.

Out of 3,208 included responses, 819 were audio recordings, and 2,389 were written responses. On average, audio recordings contained 242.73 words (SD = 79.08), and written responses contained 98.15 words (SD = 49.74).

Quantifying spontaneous thought dynamics

To quantify the dynamics of spontaneous thought, we first conducted preprocessing on the think-aloud audio recordings to transcribe the text and then split the text into individual units of thought. Finally, we grouped the individual thoughts into topics. Previous research has accomplished each of these steps using human coders (Sripada & Taxali, 2020). We developed an analysis pipeline to replicate this procedure using automated natural lan-

guage processing techniques to facilitate the processing of large datasets.

Identifying units of thought

All audio recordings were transcribed into text using Temi (www.temi.com), an automated transcription service. Three research assistants performed quality control on a subset of the data, data collection 1, to ensure audio files were transcribed correctly.

We then split each transcript and written think-aloud response into units of thought using the following automated process: We used a sentence parser to break each transcript into sentences and then identify coordinating conjunctions in each sentence (Honnibal et al., 2020). If a verb accompanied a coordinating conjunction, we considered this an independent clause. This method considers each independent clause a separate unit of thought.

To test the accuracy of this automated method, we compared the results of this method to the units identified by human coders. For this validation, human coders split 132 transcripts into units of thought following Sripada and Taxali's (2020) definition of a unit of thought as the minimal unit of text that can stand on its own as a thought. In many cases, coders could use grammatical rules to identify units of thought by splitting the transcripts into sentences and then into independent clauses. In some instances, dependent clauses or partial sentences were separate units of thought if they expressed a complete and contentful thought. Two coders processed each transcript. To compare units across the human coders and automated method, we used the SegEval Python package to calculate inter-rater reliability (Fleiss' kappa) based on boundary similarity (Fournier, 2013). Human coders showed average inter-rater reliability (Fleiss' kappa = 0.58). Human coders and the automated version showed comparable inter-rater reliability (Fleiss' kappa = 0.60). This suggests

that the automated sentence parser performs comparably to human coders. While the automated method does not have as much nuance in identifying units of thought as human coders, it performed very well. Therefore, we used the automated solution to identify units of thought in our analyses.

Identifying topic jumps

We defined a topic jump as any significant switch in time, place, and/or situation (Sripada & Taxali, 2020). Sripada & Taxali (2020) showed that a hierarchical clustering algorithm could identify topic jumps with above-chance accuracy. Therefore, we used Scikit-learn in Python to implement hierarchical clustering (Pedregosa et al., 2011) to identify which topic each unit of thought belonged to. On average, participants produced 10.82 thoughts (SD = 7.78) in 5.6 topics (SD = 4.31), with an average of 3.04 thoughts per topic (SD = 1.63).

To test the accuracy of this automated method, we compared the results of this method to the units identified by human coders on a subset of 91 transcripts. To compare topic jump coding, we again used the SegEval Python package to calculate inter-rater reliability (Fleiss' kappa) based on boundary similarity (Fournier, 2013). Here, we find that the inter-rater reliability of human coders is 0.41; interrater reliability for the human coders and the automated solution was comparable, at 0.30. While the interrater reliability is poor, even for just the human raters, the automated solution does not perform notably worse than the human coders, suggesting that the automated solution is a viable method of replacing human coders to identify topic jumps.

Defining topic switch thresholds

If the function of spontaneous thought is to optimize memory efficiency, we expect the dynamics of spontaneous thought to prioritize episodic detail. This means that topic switches should occur once thoughts on the current topic contain insufficient episodic detail. To measure the amount of episodic detail in each thought, we use an automated scoring tool initially designed for autobiographical interview narratives (van Genugten & Schacter, 2022). This software uses a fine-tuned language model to process sentences. Within each sentence, this software identifies the number of episodic details (i.e., internal details) and the number of non-episodic details (i.e., external details). When applied to the units of thought in our dataset, this yields a proportion of episodic detail for each unit of thought (# episodic details/total # of details). If spontaneous thought prioritizes episodic detail, we expect that the first thought after a topic switch has the most episodic detail, and the amount of episodic detail decreases with each subsequent thought.

Similarly, if the function of spontaneous thought is to prepare us to act according to current concerns, we expect the dynamics of thought to prioritize content related to current concerns. This means that topic switches should occur once thoughts on the current topic contain insufficient current concerns-related content. Since we did not collect data on participants' current concerns, we chose a universal concern for people during the data collection period: the COVID-19 pandemic. While this was likely a current concern for every participant in our sample, we also asked participants to indicate how concerned they were about COVID-19 on a 7-point scale. To assess pandemic-related content, we developed a dictionary of pandemic-related words. Using this dictionary, we counted the proportion of pandemic-related words in each unit of thought. If spontaneous thought prioritizes cur-

rent concerns, we expect that the first thought after a topic switch would have the highest proportion of pandemic-related words, and the proportion of pandemic-related words would decrease with each subsequent thought. We expect this effect to be stronger for participants who are more concerned about COVID-19.

We tested these hypotheses using mixed linear models of episodic detail and pandemic-related words, respectively. These models contained a fixed effect for the position of thought within a topic, with 0 being the topic switch, 1 being the thought after the topic switch, and so on. The models also included random intercepts for data collection and participant. We added a second model to test how concern about COVID-19 affects current concern-related content. This model contained fixed effects for the position of thought within a topic, concern about COVID-19, and their interaction, and random intercepts for data collection and participant.

Results

We started by testing one hypothesized function of spontaneous thought: that it serves to optimize memory. Results supported the hypothesis that the dynamics of spontaneous thought prioritize episodic detail (Figure 2.1). There was a significant effect of thought position on the amount of episodic detail in each thought, such that thoughts immediately after a topic jump had the highest level of episodic detail, and thoughts occurring later within a topic contained less episodic detail ($\beta = -0.0057, SE = 0.0019, p = 0.003$). When counting the position of thoughts until the next topic jump, we find the same pattern: the amount of episodic detail decreases leading up to a topic jump, with thoughts immediately preceding a topic jump showing the lowest level of episodic detail ($\beta = -0.0090, SE =$

$0.0019, p < 0.001$).

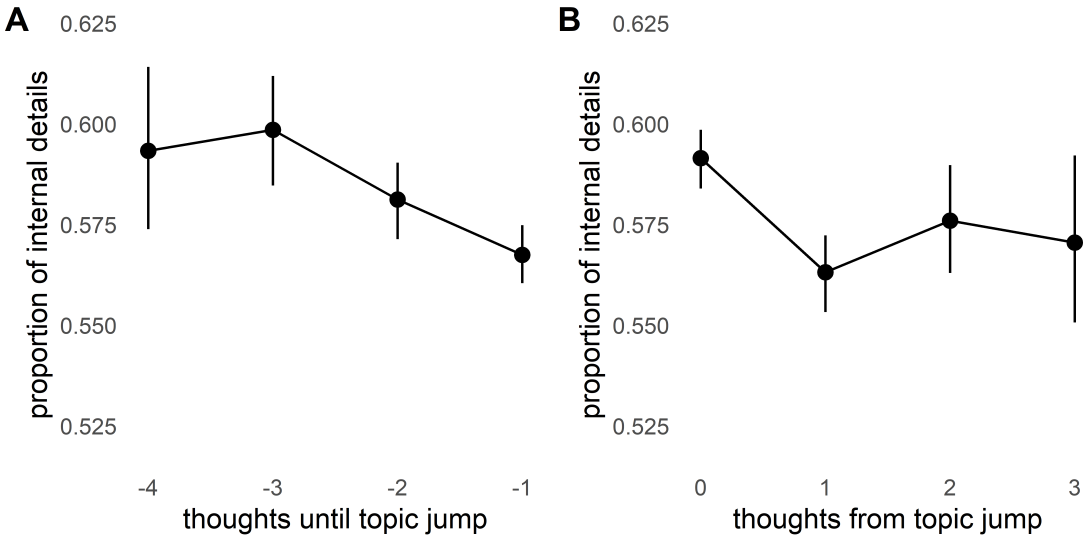

Figure 2.1: Episodic detail decreases before a topic jump (A), increases at the topic jump, and then decreases again after the jump (B)

We next tested the second hypothesized function of spontaneous thought: that it keeps us primed to act on current concerns. Results partially supported the hypothesis that the dynamics of spontaneous thought prioritize current concerns (Figure 2.2). There was a significant effect of thought position on the proportion of pandemic-related words in each thought, such that thoughts immediately after a topic jump had the highest level of pandemic-related words, and thoughts occurring later within a topic contained fewer pandemic-related words ($\beta = -0.153, SE = 0.0114, p < 0.001$). For thoughts leading up to a topic jump, the observed pattern was the opposite of what was expected. Rather than decrease until the jump, thoughts immediately before the jump showed a gradual, significant increase in pandemic-related content ($\beta = 0.120, SE = 0.0114, p < 0.001$).

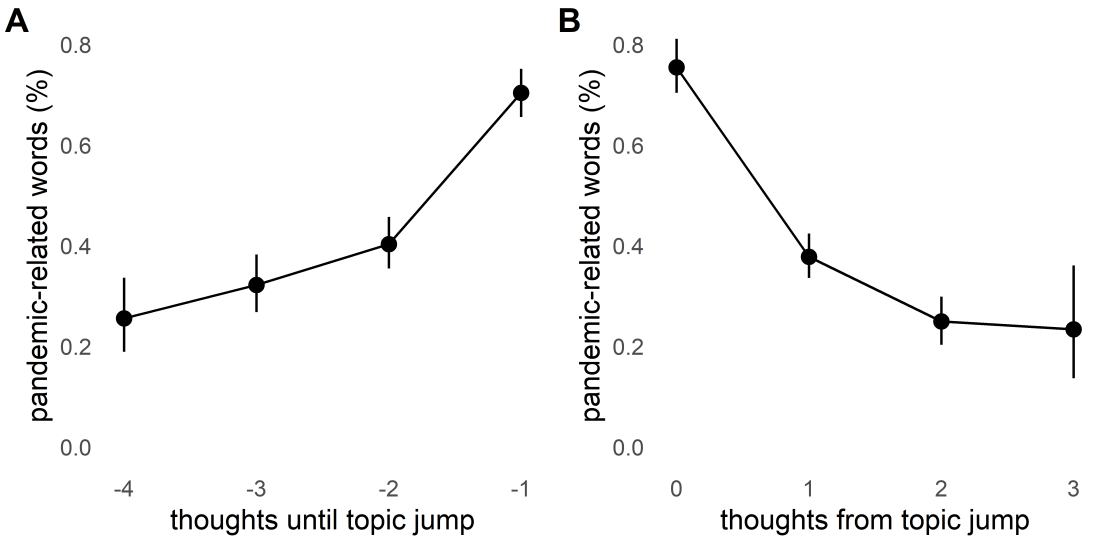

Figure 2.2: Current concerns-related content increases before a topic jump (A), then decreases after the jump (B)

Concern about COVID-19 amplified the effect of thought position on pandemic-related words, further supporting the hypothesis that spontaneous thought dynamics are optimized to focus on current concerns (Figure 2.3). We found a significant main effect of COVID-19 concern, such that participants who were more concerned had more pandemic-related thoughts overall in both the model containing thought position after the topic jump ($\beta = 0.079, SE = 0.014, p < 0.001$) and leading up to the topic jump ($\beta = 0.088, SE = 0.018, p < 0.001$). The main effects of thought position remained significant as well, with pandemic-related content decreasing after the topic jump ($\beta = -0.082, SE = 0.030, p = 0.006$) and increasing leading up to the topic jump ($\beta = 0.067, SE = 0.030, p = 0.023$). Finally, the interaction between thought position and COVID-19 concern showed that the relation between thought position and pandemic-related thought was stronger for participants with higher COVID-19 concern (after topic jump: $\beta = -0.180, SE = 0.007, p = 0.009$; leading up to topic jump: $\beta = 0.133, SE = 0.069, p =$

0.052). These results suggest that current concerns play a role in shaping the dynamics of thought, but not in the same way as episodic detail.

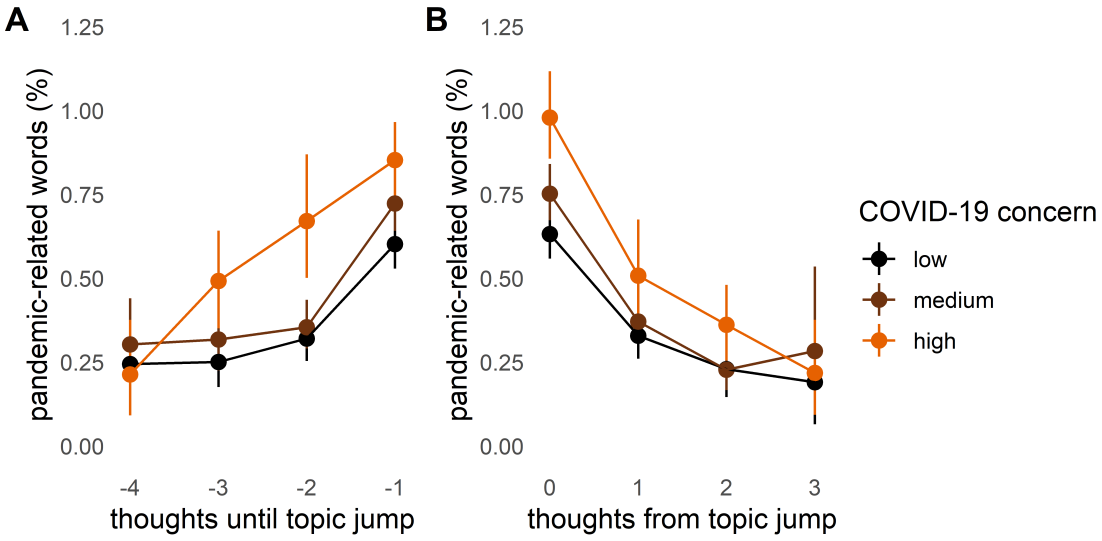

Figure 2.3: Current concerns-related content increases most before the topic jump (A) and decreases most after the topic jump (B) for participants with high concern about COVID-19. The data were binned into low, medium, and high scoring thirds for visualization purposes. Statistical analyses used the raw scores of 0-6.

Discussion

In this study, we used natural language processing of think-aloud data to gain insight into the function of spontaneous thought. We hypothesized that spontaneous thought may optimize memory function and that spontaneous thought may keep us primed to act on current concerns. We find support for both hypotheses. Episodic detail increases when thoughts switch to a new topic and then decreases within that topic until the next topic switch. Pandemic-related content, a common current concern in our dataset, follows a similar pattern: it is highest in the first thought in a new topic and then gradually decreases. However, in contrast to episodic detail, pandemic-related content increases in the thoughts

immediately preceding a topic jump. These patterns are more pronounced for participants who report high levels of concern about COVID-19. This pattern of results suggests that the function of spontaneous thought is multi-faceted: spontaneous thought prioritizes both episodic detail and current concerns.

These results join a growing body of work showing the importance of spontaneous thought for memory optimization. Activating episodic memory traces out of their original order can facilitate efficient memory storage and can help optimize semantic memory (Mills et al., 2018). Previous research has established that the content of spontaneous thought is largely episodic (Baird et al., 2011; Smallwood & Andrews-Hanna, 2013; Smallwood & Schooler, 2015; Song & Wang, 2012; Stawarczyk et al., 2013) and that spontaneous thought can facilitate memory consolidation (Mills et al., 2018; Tambini & Davachi, 2019; Wamsley, 2022). Here, we show that the dynamics of spontaneous thought appear to be optimized to support this function.

We also find strong support for the role of spontaneous thought in preparing people to act on current concerns, albeit in a partially unexpected way. Specifically, instead of thought jumps occurring when current concerns dipped below a threshold, they occurred when current concerns were at a maximum. One possible reason why current concerns-related content increases preceding a topic jump is related to one's current state. In both dreaming and waking spontaneous thought, stimuli from the external and internal environment can be incorporated into the thought content, especially if the stimuli are goal-relevant (Klinger, 1971). In our framework of spontaneous thought, this is represented in the current state layer. Pandemic-related current concerns are likely negatively valenced and possibly anxiety-inducing. Pandemic-related anxiety may be an ongoing stimulus that gets

incorporated into spontaneous thought . With the present analysis, we cannot distinguish between the extent to which the dynamics of thought inherently optimize current concerns and the extent to which the current state biases thought towards current concerns. Future work could take a more individualized approach to assess idiosyncratic current concerns, and control the extent to which they are represented in the external environment.

In this study, we applied natural language processing techniques that made it possible to analyze a large think-aloud dataset. Think-aloud data typically requires human coders to quantify the data. This approach would have been prohibitively labor intensive and expensive, given the size of our dataset. We approximated the reliability of human coders using automated sentence parsing and hierarchical clustering tools. However, reliability remained low for identifying individual units of thought and especially for identifying topic jumps. While there are clear topic jumps in our data, in many cases, human coders disagreed on the exact location of the jump, indicating a range of 2-3 thoughts rather than a single thought that constituted a clear switch. This shows room for improvement in how we define individual units of thought and topic jumps – conceptually and algorithmically. Future work should experiment with different techniques for both human coders and algorithms to increase reliability and find the most accurate way to quantify this type of data. Despite the imperfect nature of our methods, this study demonstrates that think aloud data combined with modern natural language processing tools can offer new insights into the contents and dynamics of spontaneous thought.

Applying insights from semantic foraging models allows us to identify parameters that describe the dynamics of thought. In addition to quantifying the threshold differently, future work can examine how deviations from the optimal threshold affect thought pat-

terns. For instance, if the threshold is too low, thoughts will rapidly jump from patch to patch, yielding disjointed, racing thoughts. On the other hand, if the threshold is set too high, thoughts will stay in one patch for a long time, leading to more repetitive, ruminative thought. There are likely individual differences in the threshold value people use and differences within individuals over time. These differences may help explain individual differences in creative thought (Benedek et al., 2014; Benedek & Neubauer, 2013; Mednick, 1962) or changes in thought patterns in various mental disorders (Christoff et al., 2016; Marchetti et al., 2016; Nolen-Hoeksema et al., 2008; Watkins, 2008). The foraging model's patch switching threshold parameter can be used in future work to quantify an otherwise elusive aspect of the dynamics of spontaneous thought.

Spontaneous thought makes up most of our daily cognition during wakefulness and dreaming. Here, we tested two hypotheses on why we devote so many cognitive resources to spontaneous thought: 1) spontaneous thought helps optimize memory, and 2) spontaneous thought keeps us prepared to act on ongoing goal pursuits. The dynamics of spontaneous thought support both functions. When we let our minds wander, thoughts are far from random or idle. Instead, they follow a pattern that optimizes memory function and keeps us aligned with our goals.

3

The People Around You Are Inside Your Head: Social Context Shapes Spontaneous Thought

The human mind is expansive; it is not limited by time, space, or even reality. We are capable of considering everything from the mundane to the fantastic. We can think about the sights and sounds that currently surround us, time travel into the past or far into the future. We can think about worms and wormholes, order and chaos, friends and fairies,

and everything in between. With this vast landscape of thought at our minds' doorstep, what determines the content of our thoughts at any given time?

People overwhelmingly think about other people. In a large-scale survey on the content of people's thought, 73% of respondents reported that their daydreams were primarily about other people (Mar et al., 2012). In an experience sampling study, 70% of momentary thoughts were about people (Song & Wang, 2012). Neuroimaging research likewise suggests that our minds default to thinking about social content: The network of neural regions active at rest, the default network, becomes active when people engage in explicit social cognition (Buckner et al., 2008; Fox et al., 2015; Schilbach et al., 2012; Spreng & Grady, 2009). Indeed, participants frequently think about other people during rest inside an MRI scanner (Diaz et al., 2013). Although spontaneous thought is multifaceted, social cognition is one of the clearest components of spontaneous thought (Andrews-Hanna et al., 2014). In other words, people's minds default to thinking about the social world (Lieberman, 2013; Meyer, 2019).

This focus on social thought is perhaps unsurprising given that humans are embedded in a highly social world. People in the U.S. spend 45% of their waking lives in the presence of another person, and at least 20% directly interacting with others (U.S. Bureau of Labor Statistics, 2016). Every day, people exhibit countless social behaviors, large and small, in service of their need for social connection. People choose social presence over social isolation, interact with others, groom their reputation and relationships, and serve others' needs (Baumeister & Leary, 1995; Chartrand & Bargh, 1999; Fantz, 1963; Jolly et al., 2019; Morelli et al., 2015). From simple preferences to complex and potentially costly actions, people's behaviors show a profound tendency toward the social.

When it comes to explaining the prevalence of social thought, the outsized presence of the social world raises a chicken and egg problem. Is our world social because our thoughts are inherently social, with both reflecting a fundamental need to connect with others (Baumeister & Leary, 1995; Lieberman, 2013)? Or are our thoughts social because our world is, with thoughts helping us to process our social environment?

A number of influential thinkers have argued that humans are inherently social, driven at all costs to connect with others (Baumeister & Leary, 1995; Lieberman, 2013). This account suggests that our thoughts may be social simply because we are inherently social beings. That is, people might think about the social world in order to help satiate our social needs. In this account, when the environment fails to provide people with sufficient social stimuli, the mind should fill that void by thinking about social content. There is evidence that our minds indeed work in this way: people who feel lonely attend more to social stimuli (Gardner et al., 2005; Pickett et al., 2004), and people with heightened social motivation ascribe more human characteristics to non-human entities (Epley et al., 2007). These findings suggest that the less social content in the environment, the more people engage in social thought. Moreover, these social thoughts serve their purpose of fulfilling social needs. For example, in one experience sampling study, people reported increased feelings of connectedness and happiness after they daydreamed about a loved one, but only if they lacked these positive social feelings before the daydream (Poerio et al., 2015). In another study, people completed a loneliness induction and then were randomly assigned to daydream about a close other, daydream about themselves, or complete a control task. People who daydreamed about a close other reported increased positive social feelings, love, and belonging (Poerio et al., 2016). Thus, the contents of thought can help regulate social needs. As

such, the social environment may shape social thought because it determines the extent to which social needs are met. If spontaneous social thought reflects social needs, then the less social the environment, the more social spontaneous thought. This is in line with Chapter 2's finding that spontaneous thought is optimized to keep current concerns in mind. Here, we refer to this as the *social needs hypothesis*.

However, it is also possible that people become social thinkers because they live in a social world. That is, people's thoughts might gravitate toward the social simply because the world around them is so social. Social information may propagate throughout our thoughts as a spontaneous extension of responses to environmental cues (Northoff, 2018). Environmental cues activate not just associated thoughts (Bar et al., 2007), but also associated concerns or unfulfilled goals (Klinger, 2013, 1971). As such, the social environment might be an ongoing source of cues that activate current social concerns. This focus on the social environment in spontaneous thought may help to process incoming social information (Meyer et al., 2018; Meyer, 2019) and prepare us to engage with the social world (Meyer, 2019; Spunt et al., 2015). If spontaneous social thought reflects social information in the environment, then the more social the environment, the more social spontaneous thought. This is in line with Chapter 2's finding that spontaneous thought helps optimize memory efficiency. Here, we refer to this as the *social processing hypothesis*.

The social needs and social processing hypotheses make divergent predictions about the relation between social environment and the content of thought. Here we arbitrate between these hypotheses with three studies that assess thought content in environments that span a wide range of available social information: after a period of solitude (Study 3.1), during mere social presence (Study 3.2), and after social interaction (Study 3.3). In all

three studies, we measured spontaneous thought content during mind wandering. Study 1 also assessed neural activity during social thought using fMRI. Additionally, we explored whether individual differences in social environment predict social thought (Study 3.4). These studies are presented in the order they were conducted. If the social needs hypothesis is true, social content should decrease with increasingly social environments, as the need for sociality is fulfilled. If the social processing hypothesis is true, social thought content should increase in more social environments, as the amount of external social information increases.

3.1 Study 3.1: Solitude

In this study, participants encounter no social information for an extended period of time – a seven-hour period of solitude. This allows us to measure the impact of a minimally social environment on the content of social thought, measured both behaviorally and neurally.

Methods

Data and code have been deposited on the Open Science Framework (https://osf.io/cew8b/) and are freely available. We report how we determined sample size, all data exclusions, all manipulations, and all measures in the study.

Participants

A total sample size of 80 participants, 40 per condition, was set a priori based on data from a pilot study that employed a similar solitude manipulation. Data collection stopped once that target was reached for all conditions. In the pilot data, this sample size allowed for 80%

power to detect the expected effect of interest within a neural region of interest. Participants were recruited from Princeton University's paid subject pool, which consists mostly of students, but also includes some staff and community members. To balance conditions, we scheduled control and experimental participants on the same day where possible. We collected data until we reached a sample size of 80 in the fMRI portion of the study, with participants tallied at the end of each day. We recruited a total of 87 participants (age M = 19.9, SD = 1.9, range = 18-28; 58.6% female; 36.8% White/European American, 17.2% Black/African American, 16.1% bi-racial or multi-racial, 12.6% East Asian/East Asian American, 8.0% South Asian/South Asian American, 6.9% Latino/Hispanic American) who were right handed, met the safety criteria for MRI scanning, and reported no history of anxiety or depression and no psychoactive medication. Six participants were unable to complete the scanning session due to technical difficulties (n = 3) or peripheral nerve stimulation (n = 3), leaving a total of 81 participants in the fMRI portion of this study, 39 in the solitude condition, and 42 in the control condition. All participants who complied with task instructions on the mind wandering task were included in the behavioral analyses. Participants were excluded based on the following a priori criteria, used in this and all subsequent studies: leaving more than 20% of responses blank (solitude n = 2, control n = 1), taking longer than 15 seconds to respond to a prompt more than twice over the course of the experiment (n = 0), reporting no mind wandering (i.e. paying attention to the reading) while moving through the text too quickly to read (solitude n = 3, control n = 2). The latter was operationalized as spending less than 1 second on the two pages preceding a probe, then answering "no" when asked if they were mind wandering. After exclusions, the sample size for the behavioral analyses was 79: 36 in the solitude condition, and 43 in the con-

trol condition. Informed consent was obtained from all participants in accordance with the Princeton University Institutional Review Board.

Experimental manipulation

Participants were randomly assigned to one of two conditions: solitude or control. On the day of the experiment, all participants first provided informed written consent. Participants then completed a mock MRI scanning session to ensure they were familiar and comfortable with the MRI scanning procedure. Participants in the control condition left the lab after the mock MRI session to go about their day as normal. They came back to the lab seven hours later to complete the remainder of the experiment. Participants in the solitude condition spent the next seven hours alone in a room. The room contained no reference to people or social stimuli. The room contained only puzzles, Sudoku, drawing supplies, a coloring book, a mini basketball set, and a laptop with no internet access. The laptop had non-social games, books, nature videos, and basic word processing software. Participants had no access to any other electronic devices. Snacks, water, and a lunch of the participant's choosing were provided. Participants were allowed to bring their own drawing, coloring, writing, or studying supplies. All materials in the room, including items participants brought, were screened to ensure they contained no social stimuli. Participants were instructed to put in a pair of earplugs whenever they went to the restroom, to limit their exposure to conversations in the hallway.

To ensure participants' comfort and safety, the laptop had a custom applet installed that participants could use to contact the researcher or stop the experiment. Participants were told they could use it any time they had an urgent question or wanted to stop the study

for any reason. When a participant used the applet, an alarm would go off on the experimenter's computer and the experimenter could see the participant's message and respond by sending a notification to the participant's laptop. This applet was used by 5 participants to request a fork, napkins, or feminine hygiene products or to report technical difficulties during a task.

Participants in the control condition reported on their social behaviors every hour. These participants engaged in more social interaction, as expected: They spent, on average, 102 (SD = 94) minutes interacting with other people face-to-face, and 86 (SD = 82) minutes around other people but not interacting with them. On average, they also sent 20 (SD = 24) text or instant messages, checked social media 8 (SD = 7) times, and sent 2 (SD = 3) emails.

Experience sampling

Participants completed 7 short surveys throughout the day, one at the start of the experiment (hour 0), and one at the end of every hour for the subsequent 6 hours. In the solitude condition, participants received a notification on the laptop each hour with a link to the survey. In the control condition, participants received an email with a link to the survey and could opt in to text message reminders, as well (See SI for full list of items). The experience sampling data were not analyzed as part of this paper.

Mind wandering

After seven hours, participants completed a mind wandering task in the lab. In this task, modelled off earlier work (McVay & Kane, 2012; Reichle et al., 2010), participants read

a text on the computer for a total duration of 40 minutes. The text was "Successful beekeeping A-B-C's" by Terry Martyn Jr., a text selected to be relatively boring, and to have minimal social content. Participants read the text at their own pace. Every two to four minutes, participants' reading was interrupted with a 2-item probe measuring whether or not their mind was wandering, and what they were thinking about. First, they responded "yes" or "no" to the question: "Just prior to being asked, were you mind wandering?" Next, they provided an open-ended text response to the question: "What were you thinking about?" After answering these questions, participants resumed reading the text. Each participant responded to an average of 10.98 (SD = 2.57) thought probes.

Responses to the first question of each probe served as a measure of self-reported mind wandering. Responses to the second question served as a measure of the content of participants' spontaneous thought. We quantified the social content of these thoughts using both an objective and a subjective measure. We used the same two measures in all studies.

The objective measure used Linguistic Inquiry and Word Count software (LIWC2015) (Pennebaker, 2015). LIWC counts the proportion of words in a text that fall into various psychologically relevant categories; we measured the proportion of words in each thought that fall into LIWC's "social" category, which includes words like family, friend, talk, and dance. The subjective measure of social thought was obtained using independent raters on Amazon's Mechanical Turk (mTurk). Each thought was rated by 10 mTurk raters on a scale of 1-100 to indicate how social the thought was. Specifically, raters were told to focus on mentalizing with the following instructions: "On each trial, you will rate a statement on how much it is about: reflecting on someone else's thoughts, feelings, preferences, intentions, or personality. You will rate the extent to which the statement pertains to the

thoughts and feelings of other people." Raters were excluded if they had a standard deviation of 10 points or less in their ratings (see SI for more details). Inter-rater reliability was measured using intra-class correlation (ICC). The average rating of social content served as the subjective measure of social thought. The same raters also provided ratings of task-related content, memory-based simulation, introspection, and semantic information (See SI for results on these ratings).

To measure the effect of solitude on the content of spontaneous thought, we analyzed the objective and subjective measures of social thought using a mixed-effects model for each of these variables. These models contained fixed effects for self-reported mind wandering (yes or no) and condition (solitude or control). Since each participant contributed multiple trials, the model also contained a random intercept for each participant. We did not include random slopes, to ensure model convergence.

fMRI scanning

After the mind wandering task, participants completed an fMRI scanning session. To ensure minimal social interaction for participants in the solitude condition, these participants received a notification on the computer with instructions to prepare for scanning and put in earplugs. They were then escorted to the scanner with minimal verbal instruction and eye contact. Since participants had completed mock scanning at the start of the day and they received written instructions immediately before scanning, the experimenter was able to scan participants safely and comfortably while speaking only 1-3 sentences throughout the scanning session.

Procedure. Scanning was conducted at the Princeton Neuroscience Institute with a 3 Tesla Siemens Prisma MRI scanner and 20-channel head coil. Functional scans were acquired with a T2*-weighted simultaneous multi-slice (SMS) echo-planar pulse sequence with 62 interleaved slices (TR/TE = 2250/32ms, flip angle = 70°, 128 x 64 matrix, 2.0 mm thick, field of view (FOV) = 192mm, SMS factor = 2). Participants completed 4 runs of 133 TRs each. Additionally, 6 volumes of spin echo images were acquired, with opposite phase encoding directions. These were used to calculate fieldmaps for the functional scans using FSL's Topup tool (Andersson et al., 2003). Finally, a proton density weighted structural volume was acquired (TR/TE = 8400/11ms, flip angle = 160°, 256 x 256 matrix, 1.5 mm thick, FOV = 218mm). The functional data were preprocessed using SPM12 (Wellcome Trust Centre for Neuroimaging) for motion correction and unwarping based on the fieldmap, and using the DARTEL toolbox (Ashburner, 2007) for coregistration of functional and structural volumes, normalization to MNI space, and smoothing with a 6mm FWHM kernel. Finally, low frequency noise was removed with a high pass filter (128 seconds).

Task. During scanning, participants completed a social inferences task (Tamir & Mitchell, 2012). In this task, participants judged the preferences of three targets: self, a close friend, or an unfamiliar other (i.e., Barack Obama). On each trial, participants first saw a cue that indicated the target of the judgment (e.g., self, friend's name, or Obama) for 1.5 seconds, followed by a brief statement (e.g., "enjoy browsing a book store for an hour"). Participants then had 3 seconds to rate how likely the statement was to apply to the target on a scale from 1-5, anchored on very unlikely to very likely. Participants indicated their ratings using a button box with five buttons, held in their right hand. Each statement was rated once for

the self, and once for either the close friend or the unfamiliar other. The task also included non-social control trials, where participants judged how likely an activity was to occur indoors. On these trials, participants saw the target (i.e., indoors) and a statement describing an activity for the same duration as in all other trials, and made their response using the same button box and scale. Trials were presented in randomized order, with variable fixation periods between trials. Order of trials and duration of fixation periods was optimized using Optseq2 (Dale, 1999).

During the scanning session, participants also completed a control attention task, and a task in which they shared, or privately answered questions about themselves (see SI for detailed description). All participants completed the attention task first, followed by the social inferences and sharing tasks in counterbalanced order. They then also completed a 7-minute resting state scan. These tasks and the resting state scan were not analyzed as part of this paper.

Analysis. Preprocessed fMRI data for each participant were modeled using a general linear model. The model included regressors for target (self, friend, unfamiliar other, indoors) and their temporal derivatives, as well as nuisance regressors for each of the 6 motion parameters calculated during motion correction.

To measure social thought during the social inferences task, we examined neural responses specifically within brain regions associated with social thought. To independently localize brain regions associated with social thought, we used Neurosynth (neurosynth.org), an automated meta-analysis tool, to identify regions of the brain that are associated with the terms "mentalizing" or "social cognit*". The resulting statistical map was thresholded at a false discovery rate of 0.01. From this map, all clusters with an extent of at least 20 voxels

and values in the 75th percentile or higher were extracted to form a mentalizing network ROI. This network (Figure 3.2A) included ventromedial prefrontal cortex (vmPFC), dorsomedial prefrontal cortex (dmPFC), posterior cingulate cortex (PCC), bilateral temporal parietal junction (TPJ), temporal pole (TP), and a portion of superior temporal sulcus (STS).

Results

Mind wandering

If it is the case that social context affects the content of spontaneous thought, we expected to find an interaction effect between self-reported mind wandering and condition, such that participants in the solitude condition show either increased or decreased spontaneous social thoughts, relative to control participants, specifically when they report they are mind wandering. This study did not have a priori hypotheses about the direction of the effect, nor about the specificity of the effect on social thought (vs. introspection and simulation). As such, the results here were used to arbitrate between two possible hypotheses: if solitude participants show greater social thoughts, this would provide evidence in favor of the social needs hypothesis; if solitude participants show fewer social thoughts, this would provide evidence in favor of the social processing hypothesis.

In line with the social processing hypothesis, participants in the solitude condition had fewer social thoughts during mind wandering than participants in the control condition, according to the subjective measure (Mind wandering $M_{control} = 13.47, SD_{control} = 15.12, M_{solitude} = 9.65, SD_{solitude} = 11.66$; No mind wandering $M_{control} = 12.55, SD_{control} = 11.29, M_{solitude} = 13.19, SD_{solitude} = 12.20$). That is, there was a significant negative inter-

action effect between mind wandering and condition ($\beta = -4.62, SE = 1.91, p = 0.02$). The objective measure of social thought showed a non-significant interaction between mind wandering and condition in the same direction ($\beta = -1.74, SE = 1.02, p = 0.09$; Mind wandering $M_{control} = 4.90, SD_{control} = 6.74, M_{solitude} = 3.78, SD_{solitude} = 6.28$; No mind wandering $M_{control} = 6.95, SD_{control} = 7.41, M_{solitude} = 7.57, SD_{solitude} = 7.30$). These results are in line with the social processing hypothesis: spontaneous social thought decreases after a period of solitude (Figure 3.1).

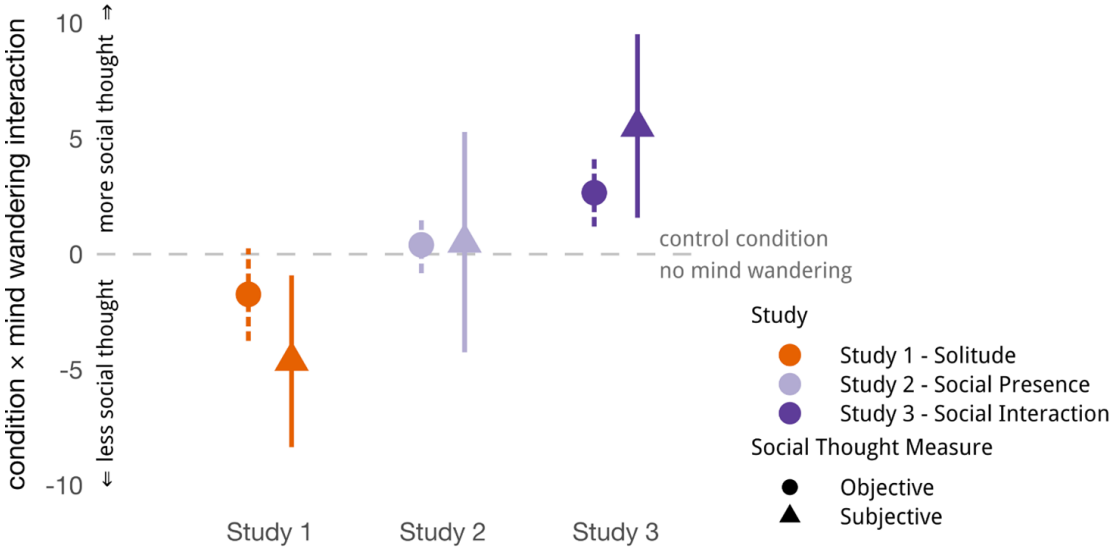

Figure 3.1: In line with the social processing hypothesis, spontaneous social thought increases in increasingly social environments. Relative to control conditions, social thought during mind wandering decreases after a period of solitude (Study 1), remains unchanged during social presence (Study 2), and increases after social interaction (Study 3). Error bars reflect bootstrapped 95% confidence intervals.

fMRI

To measure the effect of solitude on deliberate social thought, we examined neural activation in the mentalizing network while participants made social inferences. The magnitude of the activity in this network in response to each of the three targets – self, friend,

Obama – served as a neural measure of social thought. If the social processing hypothesis is supported, there would be less activation in the mentalizing network in response to social targets for participants in the solitude condition, relative to controls. If the social needs hypothesis is supported, the opposite pattern should emerge. We expect no difference between conditions in response to the control target. Again, this study had no a priori hypotheses about the direction of this effect, or about its specificity to social targets rather than the self.

The neuroimaging findings converged with the results from the mind wandering task and supported the social processing hypothesis (Figure 3.2). When making inferences about the preferences of a close friend, participants in the solitude condition had less activity in the mentalizing network than controls ($M_{solitude} = 1.072, M_{control} = 1.407, t(72.236) = 2.09, p = 0.040$). This effect was specific to the friend condition, as there were no significant group differences in this network for the self, Obama, or indoor conditions.

Together, these findings provide preliminary evidence that the social environment shapes social thought. In particular, we find that after a period of solitude, social thought decreased. The behavioral results show this effect in spontaneous thought during mind wandering, and the neural results show a similar pattern for task-related social thought about a close friend.

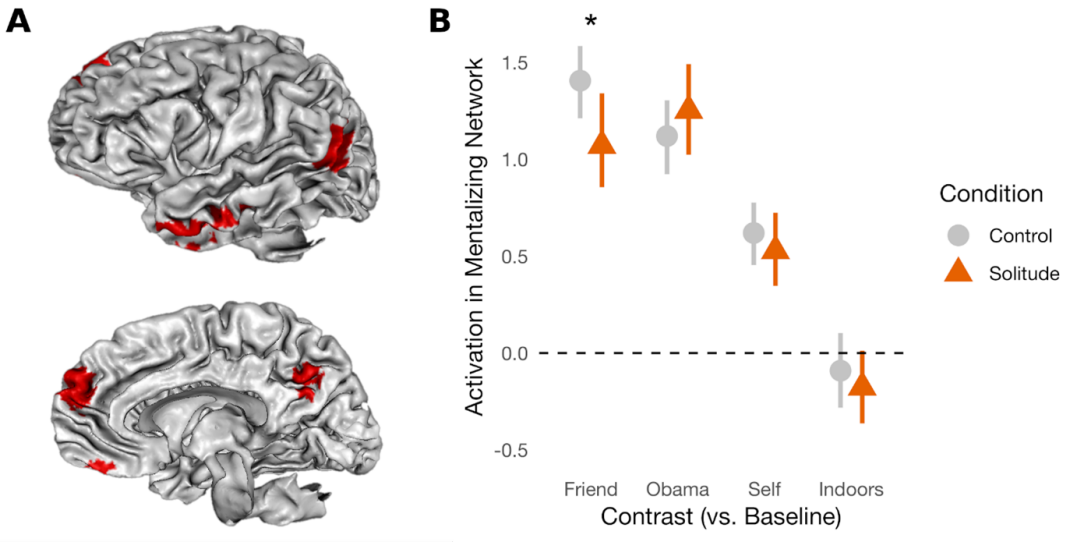

Figure 3.2: Within the mentalizing network (A), activity while thinking about a close other decreases after a period of solitude. This network shows no differences between conditions for other targets (B). Error bars reflect bootstrapped 95% confidence intervals.

3.2 Study 3.2: Social presence

If the social processing hypothesis is true and spontaneous social thought reflects the social environment, social thought should increase in more social environments. Study 3.2 measured social thought in a slightly more social environment: during mere social presence.

Methods

Participants

Target sample size was determined using a simulation-based power analysis based on the mixed model for the subjective measure of social content in Study 3.1. We used the simr package (Green & MacLeod, 2016) to add simulated data based on the observed parameters in this model. With 80 participants the simulated dataset had 878 total data points, and

an estimated 83.9% power (95% confidence interval: 81.47 – 86.13); with 95 participants and 1000 total data points, the simulated dataset had 87.5% power to detect the interaction effect observed in Study 1. We increased the sampling rate of the paradigm in Study 2 to collect 1000 total data points from 80 participants, and as such, we set a target sample size of 80 participants.

We stopped data collection once the target sample size was reached. Since participants came in in groups that were scheduled in advance, we tallied participants at the end of each study day. We recruited 91 participants from Princeton University's psychology subject pools (age M = 20.3, SD = 3.1, range = 18-35; 62.2% female; 47.7% White/European American, 23.3% East Asian/East Asian American, 13.3% bi-racial or multi-racial, 5.6% Black/African American, 4.4% Latino/Hispanic American, 2.2% South Asian/South Asian American, 1.1% Middle Eastern/Arab American). Six participants were excluded for not complying with mind wandering task instructions, using the same exclusion criteria as in Study 1, leaving a sample size of 85 participants: 42 in the social presence condition, and 43 in the control condition. One participant is included who had also completed Study 3.1. Excluding this participant did not change the results of the study.

Experimental Manipulation

Participants were assigned to either the social presence condition or the control condition. As in Study 3.1, participants in the control condition completed the task while seated in a room by themselves. The social presence condition was designed to have multiple people together, but not interacting. This condition mimicked mere presence manipulations in various previous studies (Markus, 1978; Schmitt et al., 1986; Zajonc, 1965). Participants

in the social presence condition completed the task while seated next to one or two other participants. Participants did not get a chance to interact before the task and all participants in this condition reported they did not know each other prior to the experiment. This ensured that mere presence was the only factor that differed between the two conditions.

Mind Wandering

Participants in all conditions completed the same mind wandering task from Study 3.1. To obtain more responses per participant, the task duration was extended to 45 minutes. To avoid having to exclude participants who completed the first study, we chose a different text. The text participants read in this version of the task was "A-B-C of vegetable gardening" by Eben E. Rexford (retrieved from https://www.gutenberg.org). This text contained minimal social content. Each participant responded to an average of 12.4 (SD = 1.3) thought probes.

Results

Based on the results from Study 3.1, we expected to find further evidence for the social processing hypothesis: there should be a positive interaction effect of mind wandering and condition on the subjective and objective measures of social thought. In other words, participants in the social presence condition should show increased spontaneous social thought relative to controls.

Results did not support this hypothesis. Mere social presence did not change the content of thought compared to completing the task in the control condition. There were no significant interaction effects for self-reported mind wandering and condition on either the

objective measure of social thought ($\beta = 0.44, SE = 0.46, p = 0.54$; Mind wandering $M_{control} = 3.51, SD_{control} = 4.94, M_{social\ presence} = 3.68, SD_{social\ presence} = 5.50$; No mind wandering $M_{control} = 3.55, SD_{control} = 4.55, M_{social\ presence} = 3.34, SD_{social\ presence} = 4.47$), or the subjective measure ($\beta = 0.50, SE = 2.42, p = 0.84$; Mind wandering $M_{control} = 18.27, SD_{control} = 18.87, M_{social\ presence} = 20.74, SD_{social\ presence} = 21.23$; No mind wandering $M_{control} = 17.3, SD_{control} = 16.33, M_{social\ presence} = 19.27, SD_{social\ presence} = 17.26$). These results indicate that mere social presence does not affect the social content of spontaneous thought. That said, mere social presence during a relatively short task (45 minutes) may not have added sufficient social information into the environment to alter participants' social thought. In fact, to be truly comparable to Study 3.1, participants in this study would have had to be exposed to 7 hours of mere social presence.

3.3 Study 3.3: Social interaction

Study 3.2 showed that mere social presence was not sufficient to increase spontaneous social thought, relative to being alone. It is possible that social processing prepares us to engage with others and for that reason only increases spontaneous social thought when the environment supports social interaction, rather than passive social presence. Alternatively, the mere social presence condition in Study 3.2 may be similar to the typical social environment experienced by our participants. As such, the difference in social environment between the control group and mere presence group may have been too subtle to detect any difference. Study 3.3 used a stronger manipulation of social context than Study 3.2, in an attempt to fully reverse the effect observed in Study 3.1. We preregistered the hypothesis that introducing new social information to the environment, by having participants inter-

act with each other, should increase spontaneous social thought (https://osf.io/hjfuq).

Methods

Participants

Sample size and stopping criteria were determined in the same way as in Study 3.2. This study was preregistered with a sample size of 80 participants (40 per condition). We recruited 87 participants from Princeton University's psychology credit pool (age M = 19.4, SD = 2.0, range = 18-29; 64.4% female; 40.2% White/European American, 17.2% East Asian/East Asian American, 13.8% bi-racial or multi-racial, 8.0% Black/African American, 8.0% Latino/Hispanic American, 8.0% South Asian/South Asian American, 1.1% Middle Eastern/Arab American). Two participants were excluded because they already knew each other prior to the manipulation. Three participants were excluded based on the same criteria from Studies 1 and 2, leaving a final sample of 82 participants: 40 in the social interaction condition and 42 in the control condition. One participant is included who had also completed Study 3.1. Excluding this participant did not change the results of the study.

Experimental Manipulation

Participants were assigned to one of two conditions: social interaction or control. The control condition was the same as in Studies 3.1 and 3.2: participants did the mind wandering task while they were alone, after going about their day as normal. In the social interaction condition, two participants came to the lab at the same time. They first completed the Fast Friends Procedure (Aron et al., 1997). In this procedure, the pair of participants gets index cards with questions on them. They take turns reading and answering each question out

loud. The questions are designed to elicit interpersonal closeness between two strangers. As the participants go through the stacks of cards, the questions become increasingly personal in nature. After 30 minutes, the Fast Friends Procedure ended, and participants began the mind wandering task as described in Study 3.1, while sitting side-by-side.

Mind Wandering

Participants in both conditions completed the same mind wandering task from Study 3.2, with text from "Animals of the past" by Frederic A. Lucas (retrieved from https://www.gutenberg.org). Each participant responded to an average of 11.8 (SD = 1.4) thought probes.

Results

We used the same analysis strategy described in Study 3.1 to measure the effect of social interaction on subsequent spontaneous thought content. Analyses tested the preregistered hypothesis that social interaction should increase social thought. That is, in contrast to the results from Study 1, which showed that isolated participants had less social thought during mind wandering (a negative interaction between self-reported mind wandering and condition), here we expected to see that social interaction participants have more social thought during mind wandering (a positive interaction between mind wandering and condition).

As predicted, social thought during mind wandering increased for participants in the social interaction condition relative to controls. There were significant interaction effects between mind wandering and condition on both the subjective measure of social thought ($\beta = 5.51, SE = 2.02, p = 0.007$; Mind wandering $M_{control} = 16.26, SD_{control} = 14.11, M_{social\ interaction} = 21.47, SD_{social\ interaction} = 22.03$; No mind wandering $M_{control} =$

$14.49, SD_{control} = 11.8, M_{social\ interaction} = 14.22, SD_{social\ interaction} = 12.79$), as well as the objective measure ($\beta = 2.66, SE = 0.76, p < 0.001$; Mind wandering $M_{control} = 3.83, SD_{control} = 5.11, M_{social\ interaction} = 6.44, SD_{social\ interaction} = 8.02$; No mind wandering $M_{control} = 3.46, SD_{control} = 4.75, M_{social\ interaction} = 3.54, SD_{social\ interaction} = 4.86$), such that participants in the social interaction condition had more social thought during mind wandering.

Taken together, the three studies show a pattern of increasing spontaneous social thought in increasingly social environments (Figure 3.1), where, compared to a control condition, solitude decreases social thought (Study 3.1), mere presence does not affect social thought (Study 3.2), and social interaction increases social thought (Study 3.3).

3.4 Study 3.4: Individual differences in social needs

Studies 3.1-3.3 find consistent support for the social processing hypothesis. However, it is still possible that social needs shape social thought independently of the quantity of social content in the environment. In Study 3.4, we conducted exploratory analyses that capitalize on the natural variance in participant's social environments. All participants in the control condition in Studies 3.1-3.3 (N = 128) completed the mind wandering task in the same social environment. However, they arrived at the experiment after experiencing very different social lives. We assessed the richness of their ongoing social world with measures of loneliness (Russell, 1996), need to belong (Leary et al., 2013), and tendency and efficacy in seeking out interpersonal regulation (IRQ) (Williams et al., 2018) after the mind wandering task. According to the social needs hypothesis, high scores on all of these measures should predict more social thought; lonely individuals have unfulfilled social needs, and

individuals with high need to belong and IRQ likely have high social needs by default. In contrast, according to the social processing hypothesis, high scores on need to belong and IRQ, but low scores on loneliness should predict more social thought; individuals with high need to belong and IRQ likely seek out social environments regularly, whereas lonely individuals likely inhabit less social environments. Thus, we used these individual difference measures to test these competing predictions, focusing on loneliness in particular as the measure that offers the only distinction between these two hypotheses.

Methods

Participants

All control group participants used in the first three studies were also used in this study. This made for a total sample size of 128 participants.

Measures

The content of spontaneous thought was measured both objectively and subjectively, as in Studies 3.1-3.3. Social needs were measured using the UCLA Loneliness Scale (Russell, 1996), the Need to Belong Scale (NTB) (Leary et al., 2013), and the Interpersonal Regulation Questionnaire (IRQ) (Williams et al., 2018).

The UCLA Loneliness Scale (Russell, 1996) measures loneliness in 20 items such as "How often do you feel left out?" and "How often do you feel part of a group of friends?" that participants respond to using a four-point scale of never, rarely, sometimes, or always. After reverse coding positively worded items, all responses are summed to yield a loneliness score with a maximum of 80.

The need to belong scale (Leary et al., 2013) is a 10-item questionnaire that includes items like "I want other people to accept me" and "I do not like being alone." Participants respond to these items using a 5-point likert scale of "Strongly disagree" to "Strongly agree". Responses are summed to yield a need to belong score with a maximum of 50.

The IRQ (Williams et al., 2018) measures interpersonal emotion regulation strategies in terms of tendency to seek out other people for emotion regulation and efficacy of seeking out others for emotion regulation. Tendency and efficacy are measured for both positive and negative emotions. Therefore, there are 4 subscales: tendency-positive, tendency-negative, efficacy-positive, and efficacy-negative. Each subscale is measured in 4 items, for a total of 16 items. For each subscale, responses are averaged to yield a score with a maximum of 7. The average of all items serves as an overall score.

For each of the survey scales, we fit linear models with social thought as the outcome variable and self-reported mind wandering, the survey score, and their interaction as predictors. To account for multiple observations of thought content per participant and the nesting of participants in different studies, the model also included random intercepts for each participant, and for study. As such, there were 2 models per survey measure: one for the objective and subjective measure of social thought, respectively.

The questionnaires described above are the only questionnaires related to social needs administered in these studies.

Results

Analyses of the main effect of objective measure of social thought supported the social processing account: the more an individual spontaneously thought about social content, the

lower their loneliness ($\beta = -0.066, SE = 0.027, p = 0.014$). The subjective measure of social thought showed no relation with loneliness ($\beta = -0.019, SE = 0.084, p = 0.82$). Need to belong and IRQ scores did not correlate with objective social thought (need to belong: $\beta = 0.056, SE = 0.034, p = 0.10$; IRQ: $\beta = 0.003, SE = 0.214, p = 0.98$) or subjective social thought (need to belong: $\beta = 0.183, SE = 0.106, p = 0.09$; IRQ: $\beta = 0.930, SE = 0.681, p = 0.27$). There were no significant interactions between self-reported mind wandering and survey scores, for any measure, suggesting that social thought was similarly impacted during both spontaneous mind wandering thoughts and non-mind wandering thoughts.

Since higher loneliness was correlated with fewer social thoughts, these results provide tentative support for the social processing account, and against the social needs account, although this does not appear to be specific to *spontaneous* social thought.

General Discussion

Spontaneous thoughts predominantly feature other people. Here, we examined why people's thoughts gravitate toward the social world. Are we social beings by default, driven to think social thoughts and seek out social environments by a fundamental need for social connection? Or do our social thoughts reflect our constant exposure to the social world around us? The current studies help to arbitrate between two respective hypotheses about how the social environment impacts social thought: social processing and social needs. Across three studies, we found consistent evidence for the social processing hypothesis: spontaneous social thought matches the social content available in the environment. Spontaneous social thought decreased after a period of solitude (Study 3.1), remained sta-

ble during mere social presence (Study 3.2), and increased after social interaction (Study 3.3). These findings consistently show that increasingly social environments produce increasingly social thought. This pattern of results suggests that people may think about the social world because they are so embedded in it, not because they need to.

This interpretation of the data is subject to some important caveats. First, the effect size in any individual study is small. Second, we are operationalizing social thought in two ways, using an objective and a subjective measure, which could inflate the false positive rate. Third, the effect of social isolation on social thought in Study 3.1 was only statistically significant in the subjective measure of social thought, but not the objective measure. That said, the effect of social interaction on social thought in Study 3.3 was statistically significant in both the subjective and objective measure of social thought. Moreover, the pattern of results is consistent across with the social processing account all three studies, including across both behavioral and neural measures. As such, we interpret the results as evidence for the social processing hypothesis.

The social environment likewise shaped task-related social thought. After a period of solitude, neural activation in brain regions associated with social thought decreased. This effect was specific to social thought about a socially relevant target, a close friend. Solitude did not alter neural activity while considering an unfamiliar other, the self, or a non-social target. People rely on more specific information when making inferences about a close other, and on more generic social knowledge when making inferences about a more distal other (Ames, 2004; Tamir & Mitchell, 2013; Zhao et al., 2022). This process is associated with activity in MPFC, a core hub in the mentalizing network, which responds more strongly to close others than strangers (Krienen et al., 2010; Welborn & Lieberman, 2014).

Therefore, social isolation may specifically decrease this deep, person-specific processing of social information. Future research should test how social context influences thought about more nuanced categories of social content, including content ranging in social relevance, as well as additional types of spontaneous and task-directed social thought, like theory of mind, perspective taking, and empathy.

Exploratory analyses suggested that individuals who tend to experience less social interaction in their daily life also have fewer spontaneous social thoughts. Participants with insufficient meaningful social interaction showed less social thought. This finding contrasts with previous work showing increased sensitivity to social stimuli with increased loneliness (Gardner et al., 2005). However, this finding is consistent with the social processing account to the extent that loneliness reflects less social environments. To be sure of the implications of this finding for the social processing account, future work should assess the relation between these individual difference measures and experienced – rather than inferred – social interaction. Further, it is possible that these individual difference measures are insufficient to test the social needs account. Future work should directly manipulate social needs to provide a full test of the social needs hypothesis.

Here, we found consistent evidence that spontaneous social thought reflects the social environment. This finding raises the possibility that spontaneous thought helps people to process new information in the social world. Such spontaneous processing can serve an important function: Processing new information during rest can boost memory for this information (Ellenbogen et al., 2007; Tambini et al., 2010). In a neuroimaging study, brain regions associated with social thought showed increased coupling during periods of rest that followed a social task. Moreover, this neural coupling predicted performance on a

subsequent memory test (Meyer et al., 2018). Social information from the external world propagated into spontaneous social processing during rest, and this social processing benefited retention of the new social information. Thus, it is likely that spontaneous social thought serves an adaptive purpose: It helps people integrate new social information to support later social cognition (Meyer, 2019). Future work should examine potential benefits of spontaneous social thought for social functioning.

These findings contextualize the claim that humans are social by default (Lieberman, 2013; Meyer, 2019; Schilbach et al., 2008). We may spend a majority of our time thinking about the social world (Mar et al., 2012), devote our default neural activity to social tasks (Diaz et al., 2013; Meyer et al., 2018; Schilbach et al., 2008), and make social and prosocial decisions by default (Baumeister & Leary, 1995; Chartrand & Bargh, 1999; Jolly et al., 2019). However, these defaults seem to be a *response* to the sociality of the world around us, rather than the *source* of our world's sociality. That is, people may be so doggedly social because we have learned that it is necessary to attend to the social world; this sociality may then persist because people are adept at learning the necessary social skills early in development (Atzil et al., 2018). If a person lives a day, or a life, with the din of the social world on mute, their mind will then no longer gravitate toward the social (Senju, 2013). We look forward to future work that further teases apart the extent to which our social drives are innate or just overlearned (Tamir & Hughes, 2018), perhaps by studying natural experiments in social isolation, with periods of isolation earlier in development, or longer than those studied here. The social distancing policies enforced to combat the Covid-19 pandemic may offer one such natural experiment.

Because the social world is such a profound factor in shaping much of human life (Baumeis-

ter & Leary, 1995; Fiske et al., 2010), sociality provides an ideal case for testing the role of the environment in shaping thought. However, we do not expect *only* social experiences to be reflected in spontaneous thought. Instead, spontaneous thought often reflects one's salient, important, or recent experiences, social or not. Indeed, research has shown that people (and animals) spontaneously replay recent experiences from their episodic memory during periods of quiet rest (Ellenbogen et al., 2007; Tambini et al., 2010). This memory replay is essential for optimal memory consolidation (Fachechi et al., 2019; Wamsley, 2019). Thus, the effects here are likely not limited to social information alone; non-social environmental factors or experiences should similarly shape spontaneous thought.

When people's minds wander, their thoughts overwhelmingly gravitate towards the social world. As Gazzaniga (2008) put it: "When you get up in the morning, you do not think about triangles and squares... You think about status. You think about where you are in relation to your peers. You're thinking about your spouse, about your kids, about your boss. Ninety-nine percent of your time is spent thinking about other people's thoughts about you, their intentions..." While Gazzaniga may have overestimated the extent of our spontaneous social thought, he was right that other people occupy the preponderance of our mental life. Here we shed light on the source of that preoccupation. Simply, the external social world is reflected in internal thoughts: The more social information in the environment, the more social our thoughts.

4

How does real-world social isolation affect spontaneous thought?

Despite an infinite array of possible thoughts to explore, from everyday observations and routine plans to fantastical daydreams and creative inspiration, spontaneous thought overwhelmingly features social content (Diaz et al., 2013; Mar et al., 2012; Song & Wang, 2012). Here we try to understand why the mind gravitates toward other people. We test two ways in which the environment can shape thought – does our mind review social content because the environment provides it, or does our mind seek out social content

when the environment lacks it? Prior work has suggested that spontaneous social thought helps process incoming social information from the environment (Chapter 3). However, this has not been tested in real-world, long-term changes in the social environment that can drastically impact the extent to which social needs are met.

Spontaneous thought as social processing

The social world showers people with an immense amount of social information. Spontaneous thought may offer people's minds a convenient way to process this information optimally. The dynamics of spontaneous thought are optimized to consolidate memory (Chapter 2). Replaying information during spontaneous thought improves memory for this information (Ben-Yakov & Dudai, 2011; Tambini & Davachi, 2019; Tambini et al., 2010; Wamsley, 2022). For example, in one study, participants learned new social information followed by a period of wakeful rest. Neural activity associated with social processing during this rest period predicted improved performance on a subsequent memory test for this social information (Meyer et al., 2018). Consolidating social information during rest can help prepare us to engage with the people around us (Meyer, 2019; Spunt et al., 2015). This known function of spontaneous thought may offer people an optimal way to process incoming social information from the environment. If this is the case, we would expect less social thought in less social environments. We refer to this as the social processing hypothesis (Chapter 3).

Indeed, we find evidence for this possibility in Chapter 3. In that work, we showed that social spontaneous thought decreased after a period of solitude and increased after social interaction. This finding is consistent with the idea that the social world in which people

are embedded shapes the content of their thoughts to facilitate processing of social information. Here, we aim to extend these findings beyond the lab and test if these results replicate in the real world.

Spontaneous thought and social needs

Social isolation in the real world typically lasts much longer and constitutes a more significant disruption of one's social life than the experimental manipulation in Chapter 3. It is, therefore, possible that another factor - social needs - shapes spontaneous social thought, particularly when one's social life is sufficiently disrupted. How might social needs impact social thought? The dynamics of spontaneous thought are not just optimized for memory consolidation but also prioritize content related to ongoing goal pursuits, or current concerns (Chapter 2). Since humans have a fundamental need for social connection (Baumeister & Leary, 1995), filling one's social needs is likely a universal current concern that can influence thought contents . For instance, imagining being surrounded by loved ones may help fill social needs when one is socially isolated.

There is evidence that spontaneous social thought has adaptive social and affective functions and can help fill unmet social needs (Poerio & Smallwood, 2016). When people feel lonely or disconnected, daydreaming about a loved one can increase positive social feelings (Poerio et al., 2016, 2015). This suggests that people should think more about social content when they feel socially isolated. Additionally, people who feel lonely pay more attention to social information (Gardner et al., 2005; Pickett et al., 2004); if social motives are heightened, people are more likely to anthropomorphize non-human entities (Epley et al., 2007). Stimuli in the environment can prime current concern-related thoughts (Klinger,

2013; Schertz, 2022). Since lonely people are more sensitive to social stimuli and tend to interpret non-social stimuli as social, they may be primed to think more about social content.

As such, increased social needs may cause our minds to prioritize social content during spontaneous thought. If this is the case, we would expect that social spontaneous thought increases after a period of isolation.

4.0.1 Social isolation in the real world

Real-world social contexts are much more complex than in the lab. We can distinguish between objective social isolation, also known as aloneness or solitude, and perceived social isolation, or a dissatisfaction with the quality of social life, also known as loneliness. In 2019, adults in the U.S. spent about 40-55% of their waking hours alone. Older adults spent the most time alone. In 2020, during the COVID-19 pandemic, aloneness increased to 47-59% of waking hours (United States Bureau of Labor Statistics, 2021).

While being alone is a common everyday occurrence, people's experiences of being alone can vary wildly (Larson, 1990; Long et al., 2003). The word solitude has largely positive connotations (Hipson et al., 2021), and being alone can be a positive experience for people who intentionally seek it out (Coplan & Bowker, 2013; Long & Averill, 2003). For example, when people are motivated to spend time alone, solitude has been linked to relaxation (Nguyen et al., 2018), improved well-being (Chua & Koestner, 2008), higher self-esteem (Nguyen et al., 2019), and decreased loneliness (Chua & Koestner, 2008; Nguyen et al., 2019, 2018). However, being alone can also have negative consequences (Coplan & Bowker, 2013). While alone, people experience less high arousal affect (Nguyen et al., 2018), which can lead to feelings of passivity and boredom (Larson, 1990). Spending too

much time alone has been linked to loneliness and depression (Hawkley & Cacioppo, 2010).

Objective and perceived isolation do not always co-occur and are only weakly to moderately correlated (Cho et al., 2019; Coyle & Dugan, 2012). Lonely people do not spend more time alone than others (Hawkley et al., 2003; Queen et al., 2014). People can experience high social connectedness while objectively isolated or feel lonely in a crowd of people. While both objective and perceived social isolation are associated with increased morbidity and mortality overall, these effects are strongest for perceived social isolation (Cacioppo & Hawkley, 2003; Cho et al., 2019; Friedler et al., 2015; Hawkley & Cacioppo, 2010; House et al., 1988; Valtorta et al., 2016).

In Chapter 3, we manipulated the objective social environment and did not find support for the social needs hypothesis since spontaneous social thought decreased after a period of isolation. However, the 7-hour social isolation manipulation did not affect perceived social isolation or loneliness. In other words, manipulating the social environment in this manner may not have been sufficient to affect the extent to which social needs are met. Therefore, to test the social needs hypothesis, we need to examine spontaneous social thought in a context strong enough to impact perceived social isolation rather than just objective social isolation.

Current Studies

Here, we test the social processing and social needs hypotheses in large, real-world disruptions of the social environment. In Study 4.1, we analyze the relation between spontaneous social thought and social environment and social needs in a large dataset collected during

the COVID-19 pandemic. In Study 4.2, we analyze literary works from authors who experienced social isolation in the form of imprisonment, exile, or seclusion. If in the real world, the social needs hypothesis is true, we expect to see more social thought in participants whose social needs were not sufficiently met during the pandemic and more social content in literary works written in involuntary isolation. If the social processing hypothesis translates to real-world social isolation, we expect less social thought when participants spent more time alone during the pandemic and less social content in literary works written during voluntary isolation.

4.1 Study 4.1: The contents of spontaneous thought during the COVID-19 pandemic

The social environment shapes spontaneous thought. In Chapter 3, we showed that the social content of spontaneous thought reflects the objective social environment. However, the lab studies in Chapter 3 were limited to short-term, relatively minor changes in the social environment. It is possible that in the real world, large, long-term disruptions in the social world affect social needs more strongly and, therefore, also affect spontaneous social thought differently. When the COVID-19 pandemic led to lockdowns and quarantines worldwide, people's social lives were disrupted at an unprecedented scale. This presented a new test case for our hypothesis that the content of spontaneous thought reflects the social environment (Chapter 3).

This study used a large-scale longitudinal survey to assess people's objective social environment and social needs through the COVID-19 pandemic. We measured spontaneous thought using a think-aloud task. This approach allows us to directly compare the effects

of objective social environment and social needs on spontaneous thought in a large, representative sample.

Methods

Participants

We collected 3,332 responses from 1,679 participants (mean age = 39.8, range [19.0 – 79.0], 15.9% Asian/Asian American, 14.1% Black, 7.0% Latinx, 1.0% Native American, 65.7% White, 56.6% women, 1.3% genderqueer/non-binary/other) in three separate data collections between April 2020 and May 2021. All participants completed the study online on their own devices (mobile, tablet, or computer). Informed consent was obtained from all participants in accordance with the Princeton University Institutional Review Board.

Data collection 1. We collected 532 responses from 371 participants between April and July 2020. The study link was advertised on Princeton University email lists and social media as a study on social distancing. Princeton University announced its first COVID-19 lockdown on March 11, 2020, and started virtual instruction on March 23, 2020. After completing the study, participants were asked if they wanted to receive email invitations to participate again periodically. Invite emails were sent to previous participants once a week initially and every other week after that. Participants could access the study with their participant ID at least five days after their most recent entry. In total, 371 participants consented, and 82 participants completed the study 2-6 times.

Data collection 2. We recruited 273 participants through the Chicago Booth Center for Decision Research subject pool. Participants were asked to participate twice: once be-

tween April 14 and 23, 2020, and once between May 11 and 23, 2020. They were paid $4 for each time they participated. Illinois issued a stay-at-home order starting on March 21, 2020.

Data collection 3. Finally, we recruited 1,023 participants through Prolific Academic (www.prolific.co) in May 2020. These participants were a representative sample matched to U.S. census values for sex, age, and ethnicity. We invited the same people to participate again in June 2020 and April 2021. In wave 2, 831 participants returned; in wave 3, 477 participants returned.

Totals & Exclusions. We combined data from all three data collection efforts for a total of 3,332 responses from 1,679 participants. We excluded participants who did not provide usable think-aloud data, defined as using fewer than 25 words or more than 500 words (n = 125). We also excluded participants who provided responses more than three standard deviations above the mean on the measures of household size (n = 12) or the number of close others (n = 32). The final sample size for this study was 3,188 responses from 1,616 participants.

Measures

This study was conducted as part of a larger data collection effort. Participants completed up to 10 measures, including this survey's key measures, assessing spontaneous thought, social environment, and social needs. Findings from other measures in the survey are available elsewhere.

Social thought. We measured the contents of spontaneous thought using a think-aloud task, where participants either narrated their thoughts out loud into their device's microphone or typed their thoughts into a text box. See Chapter 2 for details on this task. We used Linguistic Inquiry and Word Count software (LIWC-22) (Pennebaker et al., 2022) to count the proportion of social words in each transcript or written response, the same approach used in Chapter 3.

Social environment. Participants reported on their physical social environment by indicating how many hours they had spent on each of the following activities in the past 24 hours: (i) Awake and all by yourself (e.g., working, reading, driving, cleaning, personal care, etcetera, while nobody else is in the same room), (ii) Awake and by yourself while interacting with other people online or on the phone (e.g., talking on the phone, video calling, playing online multiplayer games, texting, instant messaging, etcetera), (iii) Interacting with others face-to-face, (iv) Around other people in the same physical space, but not interacting with them (e.g., in a coffee shop, library, office building, bus, gym, waiting room, store, etcetera), and (v) Sleeping.

Participants were told that their responses should add up to 24 hours total. For their convenience, they were shown the total number of hours they had allocated and could not advance to the next page until their responses added up to 24 hours.

To measure physical social isolation, we subtracted the number of sleeping hours from 24 to obtain the number of waking hours. Then, we calculated the proportion of waking hours each participant spent alone and not interacting with anybody. As another measure of the physical social environment, participants also reported how many people lived in their households.

Social needs. To assess social needs, participants completed measures of loneliness and social support. Loneliness was measured using the UCLA Loneliness Scale. The UCLA Loneliness Scale (Russell, 1996) consists of 20 items such as "How often do you feel left out?" and "How often do you feel part of a group of friends?" Participants respond using a four-point scale of never, rarely, sometimes, or always. After reverse coding positively worded items, all responses are averaged to yield a loneliness score between 1 and 4.

We measured social support using the Medical Outcomes Study (MOS) Social Support Survey (Sherbourne & Stewart, 1991). This survey consists of one item that asks participants to report how many close friends and family members they have, followed by 19 items that assess how often different types of social support are available. Participants use a scale of 1 (None of the time) to 5 (All of the time) to indicate how often they have access to social support, such as: "Someone to help you if you were confined to bed," "Someone who hugs you," or "Someone who understands your problems." Responses to these 19 items were averaged to yield a social support score between 1 and 5.

Analysis

Our primary analyses assessed the relation between spontaneous social thought and our measures of social isolation and social needs, respectively. We used mixed linear models to analyze the data. We fitted separate models for each of the social isolation variables (i.e., time spent alone, household size) and social needs variables (i.e., loneliness, number of close others, and social support) with the number of social words as the outcome variable and the social isolation and social needs independent variables as a fixed effect. Each model included random intercepts for the dataset and participant ID to account for possible differ-

ences in data collection and repeated measures.

Results

We first tested if the amount of objective social isolation predicted spontaneous social thought. We used the time spent alone and household size as measures of the objective social environment. In line with the social processing hypothesis, we found that social environment affected social thought such that the more time spent alone in the past 24 hours, the less social thought (Figure 4.1). This effect was small but statistically significant ($\beta = -0.085, SE = 0.019, p < 0.001$). We did not find an effect on social word usage for household size ($\beta = 0.007, SE = 0.020, p = 0.73$).

We next tested if social needs affected spontaneous social thought. We used loneliness, the number of close others, and social support as subjective measures of social fulfillment. Results did not support the social needs hypothesis. Social thought was not significantly related to measures of loneliness ($\beta = -0.023, SE = 0.020, p = 0.25$), number of close others ($\beta = 0.030, SE = 0.021, p = 0.16$), or social support ($\beta = -0.001, SE = 0.035, p = 0.97$). If anything, the findings ran directionally counter to the social needs hypothesis; people who were lonelier and with fewer close others showed less social thought.

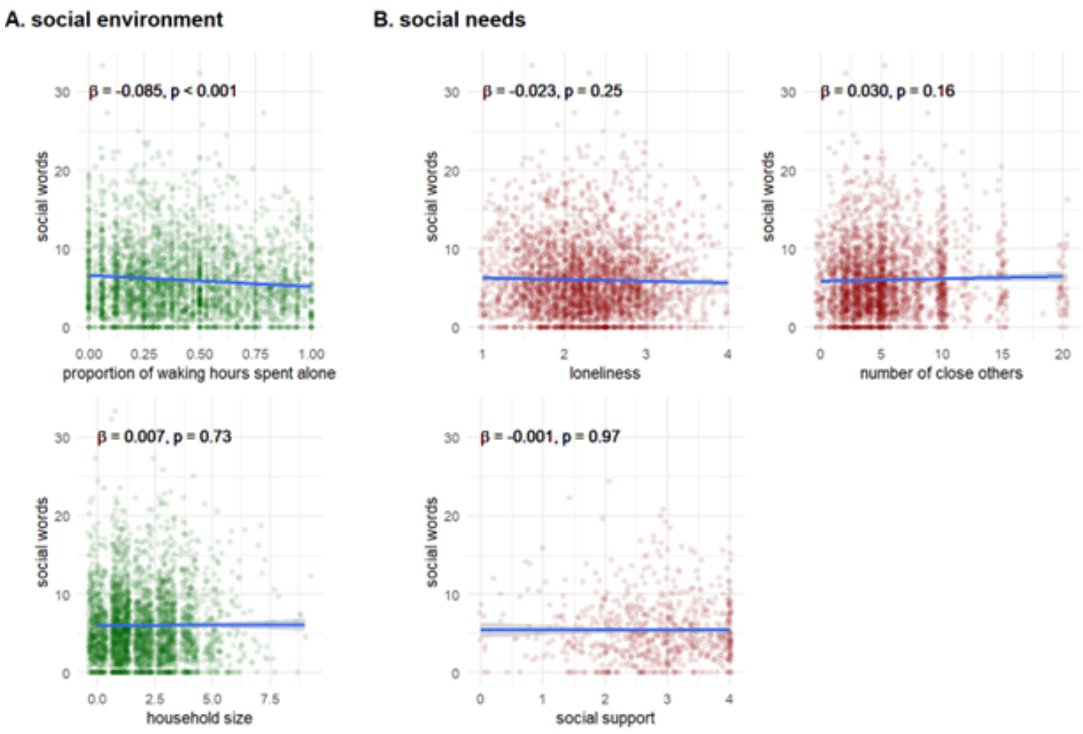

Figure 4.1: (A) Social environment affects social thoughts: the more time participants spent alone in the last 24 hours, the fewer social words they used in their spontaneous thought. This effect did not hold for household size. (B) There was no relation between any of the social needs variables and social thought.

Discussion

Here, we re-examined the relation between the social world and social thought during a real-world disruption of people's social lives. This study found that the amount of objective social isolation but not social needs affected spontaneous social thought during the COVID-19 pandemic. These results suggest that spontaneous thought reflects the social content in the environment, in line with the social processing hypothesis (Chapter 3): the more time people spend alone, the less social their spontaneous thought.

During the pandemic, people could use virtual communication to maintain crucial so-

cial relationships. While participants in this sample experienced a large disruption in their physical social environment, the disruption in their perceived social environment may not have been as large. The evidence on how the COVID-19 pandemic affected perceived social isolation is mixed. Early evidence from COVID-19-related lockdowns showed no increases in loneliness (Luchetti, 2020). Other studies found increased loneliness (van Tilburg et al., 2021), especially when considering a perceived lack of physical social contact, such as hugging or being among a crowd of people (Landmann & Rohmann, 2022). It is possible that both social processing and social needs affect the content of thought but work against each other in these data. Given the relatively subtle effects of the pandemic on the extent to which social needs were met, it is possible that the effects of the social environment on thought content were simply larger than the effects of social needs in this case.

4.2 Study 4.2: Literary authors in social isolation

In Chapter 3 and Study 4.1, we showed that spontaneous social thought reflects social processing: during objective social isolation, spontaneous social thought decreases. However, the dynamics of spontaneous thought support not only the processing of new episodic information but also current concerns (Chapter 2). We would therefore expect that social needs can also shape thought, such that social thought content increases during perceived social isolation. To put the social needs hypothesis to an even more rigorous test, people's social lives should be disrupted significantly enough to affect the extent to which social needs are met. Since such disruptions are impossible and unethical in experimental studies, here we turned to people who have experienced large disruptions in their social world and left behind evidence of their experiences.

We analyzed archival data to test whether social needs affect social thought. Specifically, we collected works written during periods of relative isolation and compared those to texts written by the same authors in their regular social environments. We included authors who experienced involuntary isolation, i.e., imprisonment or exile, and authors who experienced voluntary isolation, i.e., seclusion. Involuntary isolation is a powerful test of the social needs hypothesis. While incarcerated individuals tend to live in a group setting and therefore do not necessarily experience objective social isolation, imprisonment does lead to perceived social isolation and loneliness (Carlton & Segrave, 2011; Schliehe et al., 2021). In contrast, authors in voluntary isolation are likely having more positive solitude experiences that do not affect the extent to which social needs are met. Here, we expect that authors who experienced voluntary isolation produce less social content, in line with Chapter 3 and Study 4.1. Conversely, authors who experienced involuntary isolation are expected to produce more social content as their social needs are unmet.

Methods

We first identified authors who had experienced some form of social isolation using a web crawler on Wikipedia's list of authors by name (`https://en.wikipedia.org/wiki/List_of_authors_by_name:_A`) and list of poets by name (`https://en.wikipedia.org/wiki/List_of_poets`). For each author on the list, we scraped their Wikipedia entry, looking in particular for words related to social isolation. The keywords we used were solit*, prison, exile, hermit, isolat*, adrift, marooned, secluded, seclusion, and reclus*. These keywords yielded 428 author matches.

We manually checked each match to confirm if they i) experienced isolation during that

period and ii) wrote during that period. We identified 44 authors who experienced isolation and had written works both when they were isolated and when they were not isolated. We collected 142 texts written in isolation and 104 control texts from the same authors. These texts spanned a range of genres: fiction (n=108), non-fiction (n=59), letters (n=37), poetry (n=36), plays (n = 1), speeches (n=3), and other (n = 2). Most texts were written in the 20th century (n =125), some in the 19th century (n=81), some before the 19th century (n = 30), and the remainder in the 21st century (n=10). The type of isolation experienced by the authors fell into three categories: exile (8 authors, 37 texts), prison (28 authors, 73 texts), and seclusion (13 authors, 33 texts). For our purposes, we distinguish between voluntary isolation, which is less likely to impact social needs (i.e., seclusion), and involuntary isolation, which is likely to impact social needs (i.e., exile or imprisonment).

Analyses

Classifier. We conducted two sets of analyses to test for differences in content between involuntary isolation, voluntary isolation, and control. First, we aimed to detect differences in language use in social isolation compared to control texts. To do so, we trained a multinomial Naïve Bayes classifier on bag of words features of each text (i.e., the number of times each word appeared in each text) using scikit-learn in Python (Pedregosa et al., 2011). This classifier learns the probability of each feature (word) appearing in documents of each category (isolation and control) based on training data and uses that to predict which category a new document most likely belongs to. We performed leave-one-out cross-validation to test the classifier's performance compared to chance. If social isolation affects the contents of written works, we expect the classifier to pick up on this difference and accurately predict

whether or not a text was written during isolation.

Content. The classifier method can tell us if there are differences in word usage between isolation and control but offers little insight into what those differences are. To test the usage of social words specifically, we next used keyword-assisted topic modeling (Eshima et al., 2021). This is a Bayesian semi-supervised topic model that allows for the specification of keywords for topics before fitting the model, rather than labeling the topics post hoc. These analyses were conducted using the keyATM package in R (Eshima et al., 2022). We used the LIWC2015 dictionary for social words (Pennebaker, 2015) combined with a mind perception dictionary (Schweitzer & Waytz, 2021) to establish a 'social' topic before fitting the topic model. We then fit the keyword-assisted topic model with the type of isolation (voluntary, involuntary, or none) as a covariate. The model included the keyword-assisted social topic and five other topics with no a priori keywords to improve model fit. After fitting the model, we used it to estimate the predicted topic proportion (θ) for each covariate level.

If the social processing hypothesis extends to long-term real-world isolation, we expect θ for the 'social' topic to be higher in the control texts than in the isolated texts. If instead, long-term social isolation activates social needs, we expect θ for the social topic to be higher in the isolated texts than in the control texts. Additionally, involuntary isolation should lead to a greater increase in social needs than voluntary isolation since authors who choose to be socially isolated likely have less need for social connection than others. Therefore, if the social needs hypothesis is true, we also expect θ for the social topic to be higher for texts written during involuntary isolation compared to voluntary isolation or control.

Results

Classifier

We first tested if there is a detectable difference between content produced during isolation compared to control using text classification. As expected, the Naïve Bayes classifier predicted whether a text was written in isolation with above-chance accuracy (60.6% accuracy, chance accuracy = 51.5%, p = 0.006), indicating there is a detectable difference between the words used in isolation compared to control.

Content

We next tested if isolated authors produced more or less social content using a keyword-assisted topic model. The keyword-assisted topic model for isolation vs. control yielded tentative support for the social needs hypothesis. The mean estimated proportion (θ) of social topic words was higher for texts written in isolation ($M = 0.403, 90\%\ CrI\ [0.374, 0.429]$) compared to control ($M = 0.367, 90\%\ CrI\ [0.338, 0.397]$), though the 90% credible interval of this difference included 0 ($M_{diff} = 0.036, 90\%\ CrI\ [-0.004, 0.075]$).

We then tested if the prevalence of the social topic differed between voluntary and involuntary isolation using another topic model with type of isolation (voluntary, involuntary, or none) as a covariate. The model for voluntary isolation, involuntary isolation, and control showed that this effect was driven entirely by involuntary social isolation (Figure 4.1). Social topic words were more common in texts written in involuntary isolation ($M = 0.415, 90\%\ CrI\ [0.367,\ 0.473]$) compared to both voluntary isolation ($M = 0.304, 90\%\ CrI\ [0.220, 0.385]$) and control ($M = 0.357, 90\%\ CrI\ [0.327, 0.387]$).

The difference between involuntary and voluntary isolation reached statistical significance ($M_{diff} = 0.109,\ 90\%\ CrI\ [0.031, 0.199]$), but the difference between involuntary isolation and control did not ($M_{diff} = 0.065,\ 90\%\ CrI\ [-0.032, 0.110]$).

In contrast, social words were less common in texts written in voluntary isolation than in control, but this difference did not approach significance ($M_{diff} = -0.065, 90\%\ CrI\ [-0.135, 0.049]$). This suggests that the social needs hypothesis holds only for involuntary social isolation.

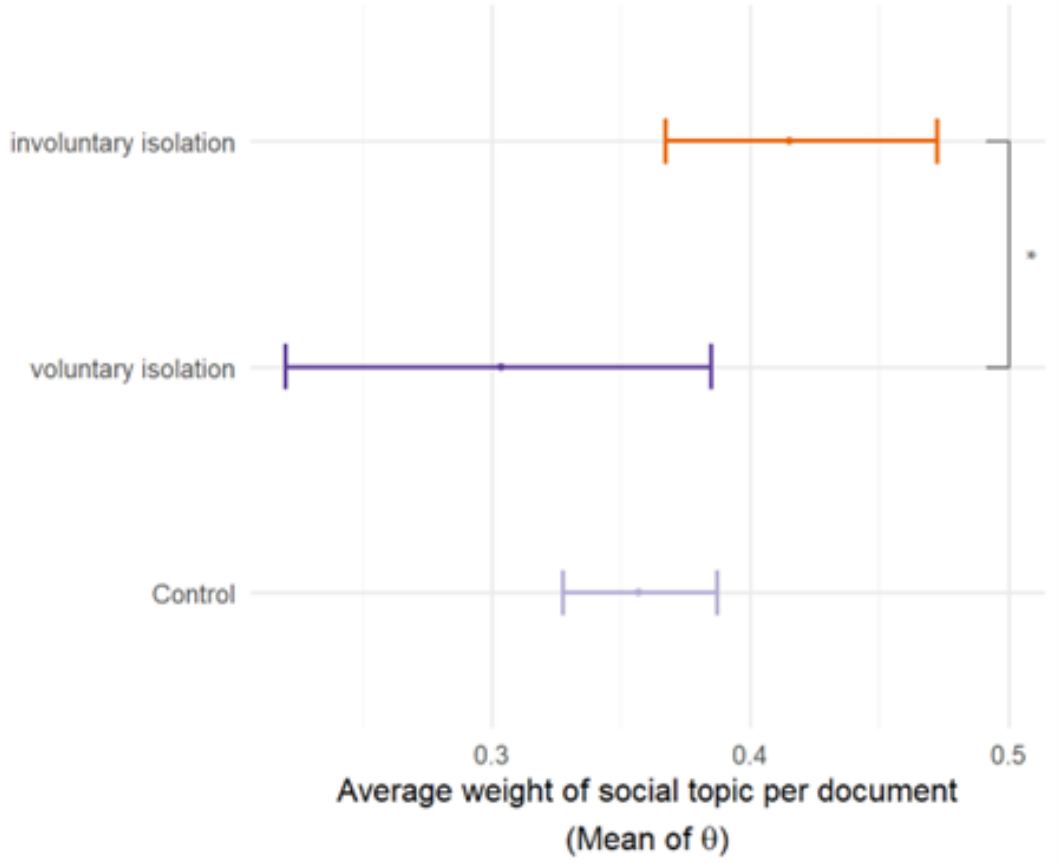

Figure 4.2: The social topic is more likely to appear in texts written during involuntary social isolation than in those written during voluntary isolation. There were no differences between the control condition and either of the isolation conditions.

Discussion

This study provides some support for the social needs hypothesis: authors who were isolated wrote more social content in their works, specifically if this isolation occurred involuntarily. This study offers a strong test of the social needs hypothesis by capturing social thought in a population experiencing long-term, real-world isolation. In this context, we find reliable evidence that individuals whose social needs are not being fulfilled by real-world social interaction may supplement their lack of social contact with social thoughts.

General Discussion

Spontaneous thoughts gravitate towards social content. In this chapter, we examine whether the content of our thoughts is shaped by our physical social environment or by our inherent social needs. Study 4.1 showed that during the COVID-19 pandemic, physical social isolation but not social needs shaped spontaneous thought. The more time participants spent by themselves prior to recording their thoughts, the more social their spontaneous thought. There were no relations between social needs variables and spontaneous social thought.

The results of Study 4.1 were in line with the findings from Chapter 3: participants in less social environments had less social spontaneous thought. In this study, we used a large representative sample to collect data on real-world experiences of objective and perceived social isolation. There were no effects of social needs on the contents of thought. This suggests that spontaneous thought can serve to process incoming social information from the environment. This is in line with the idea that spontaneous thought helps to optimize memory by replaying recent episodic experiences (Chapter 2).

In contrast, in Study 4.2, archival analysis of texts written during various forms of isolation showed that texts written during involuntary isolation, such as imprisonment or exile, contained more social content. This is in line with the hypothesis that spontaneous thought can help fill social needs in environments that do not offer sufficient social connection. Taken together, these results suggest that both social needs and social processing can shape the contents of our thoughts.

While participants in Study 4.1 did experience changes to their objective social environment, they may still have had the opportunity to fill most of their social needs, for example, by utilizing opportunities for virtual social interaction. Study 4.2 offers a stronger test of the social needs hypothesis by examining involuntary social isolation, which is typically associated with loneliness. Results from Study 4.2 suggest that when the perceived social environment is sufficiently disrupted, social needs to shape the social content of thought. Together with the results from Chapter 3 and Study 4.1, this suggests that the social processing hypothesis is true for small, short-term variations in social environment, and the social needs hypothesis is true for large, long-term variations in social environment.

Additionally, these findings highlight the difference between objective and perceived social isolation (Cacioppo et al., 2011). In this study, we had no measure of the objective social environment of the authors. While imprisonment is a massive change from one's regular social environment, most prisoners live in a group setting and are therefore isolated only from their loved ones, not from people in general. The authors who experienced voluntary social isolation likely have the opposite experience where they are in objective social isolation, but their social needs are not significantly disrupted. The pattern of results does suggest that authors in voluntary isolation produce less social content, in line with the so-

cial processing hypothesis. However, the sample of authors in voluntary isolation is too small to draw firm conclusions. Future research should increase the sample size, balance conditions and genres, and incorporate more information on the physical social environment, for example, comparing solitary confinement and general population imprisonment.

Overall, this chapter suggests that while the contents of our thoughts generally reflect our everyday social environment, sufficiently large disruptions to our social world interfere with this pattern such that the contents of our thoughts reflect unmet social needs instead.

Study 4.2 also raises the possibility that social isolation differentially affects spontaneous and goal-directed thought. Written works typically do not reflect purely spontaneous thought. With the possible exception of the stream of consciousness genre, literary works are a product of goal-directed thought. Since authors in involuntary isolation are displaced from their community, their works may be disproportionately written with the explicit goal of communication with loved ones about inherently social topics, such as prison life and themes of social justice. One example of such content in our dataset are Nelson Mandela's letters from prison. In fact, out of 37 letters in our dataset, 26 were written during involuntary isolation and only one during voluntary isolation. In contrast, the vast majority of works in the voluntary isolation group were works of fiction or poetry (85%) compared to only about half the works in involuntary isolation (52%). Poetry and fiction may contain more creative ideation than letters and other non-fiction texts. Since creative ideation is a form of spontaneous thought, future research with a larger dataset could use genre as a measure of the goal-directedness of thought.

These results add nuance to the results from Chapter 3. In settings like imprisonment, where there is more perceived social isolation than objective social isolation, thought may

reflect social needs. In settings where the connection with loved ones is not as badly disrupted, thought reflects social processing.

5

Conclusion

Most of mental life consists of spontaneous thought, like daydreams and unbidden imagery. These spontaneous thoughts are a window into the human mind, yet they are notoriously difficult to capture empirically. This dissertation offers a theoretical framework that recasts spontaneous thought as an unconstrained memory process. In this framework, semantic memory scaffolds episodic simulation to form the main content of spontaneous thought. Episodic simulations unfold until the active memory space becomes depleted, at which point, thoughts ride on a drifting internal context that is influenced by one's current state to find new memories to explore. In three chapters, we use this frame-

work to investigate the dynamics and content of spontaneous thought.

First, we investigate why our minds dedicate so much time and cognitive resources to spontaneous thought. There are two leading hypotheses about the function of spontaneous thought: memory optimization and current concerns. Under the memory optimization hypothesis, spontaneous thought reflects a replay of recent episodic events designed to optimize episodic memory efficiency and extraction of semantic knowledge. Under the current concerns hypothesis, spontaneous thought keeps us prepared to act according to our ongoing goal pursuits, or current concerns, by keeping goal-related content at the forefront of our thoughts. Throughout this dissertation, we tested how these possible functions of spontaneous thought are reflected in the dynamics (Chapter 2) and contents (Chapters 3 and 4) of spontaneous thought.

Current findings

Chapter 2 aimed to quantify the dynamics of spontaneous thought to test if those dynamics are optimized for memory consolidation or activating current concerns. First, we used natural language processing techniques on think-aloud data to segment the stream of thought into units of thought that are clustered in topics. Then, we examined how the levels of episodic detail and content related to current concerns change before and after topic jumps. We showed that the dynamics of spontaneous thought through memory space prioritize episodic detail, consistent with the hypothesis that spontaneous thought is optimized to facilitate memory consolidation and semantic abstraction. The dynamics of spontaneous thought similarly prioritize content related to current concerns, although the pattern in the data suggests that this may be partially due to the influence of the current

state on thought. This chapter provided empirical evidence that the dynamics of thought support both memory optimization and processing of current concerns.

In Chapter 3, we examine how the external social environment shapes the content of spontaneous thought. Since sociality is a universal theme in the external environment and in the content of thought, we examine how the people around us affect social content in spontaneous thought. In other words, we use sociality as a test case for the influence of the external environment on spontaneous thought. This chapter tested the memory optimization and current concerns hypotheses in the context of the relation between social environment and social thought. To do so, we tested the social content of spontaneous thought in varied social environments: solitude, social presence, and social interaction. Results were consistent with the memory optimization hypothesis: social thought decreased after a period of isolation and increased after social interaction, reflecting the processing of incoming social information.

Chapter 4 attempted to replicate the findings from Chapter 3 in real-world contexts while simultaneously providing a stronger test of the current concerns hypothesis, which predicts that social content in thought reflects the extent to which social needs are met. While Chapter 3 manipulated the objective social environment, Chapter 4 examined large disruptions to both objective and perceived social environments in the real world. Survey data collected during the COVID-19 pandemic supported the memory optimization/social processing hypothesis: objective social isolation predicted less social content during spontaneous thought, whereas social needs did not correlate with spontaneous social thought. Archival analysis of texts written during various forms of social isolation supported the current concerns/social needs hypothesis: authors in involuntary isolation (e.g., prison or exile)

used more social content in their writings than authors in voluntary isolation (e.g., seclusion). These findings further support the memory optimization hypothesis while highlighting a potential role for social needs in shaping the contents of thought when the perceived social environment is massively disrupted.

The function of spontaneous thought

Throughout Chapters 2-4, we show consistent support for the hypothesis that spontaneous thought optimizes memory while simultaneously prioritizing current concerns-related content when necessary. Based on our findings, both the dynamics and contents of spontaneous thought reflect the processing of incoming episodic information. The dynamics of thought also reflect a focus on current concerns. Still, this pattern is not entirely consistent with optimal processing of current concerns but rather with the idea that the environment injects goal-relevant content into thought. The contents of thoughts similarly show a more nuanced influence of current concerns. The content of thought only prioritizes current concerns over memory processing in cases where basic social needs are unmet. Future work should measure individual current concerns and their effect on the dynamics and contents of thought to investigate under what circumstances current concerns shape spontaneous thought.

Quantifying spontaneous thought

Due to its unconstrained nature, spontaneous thought is difficult to capture empirically. Questionnaires (Diaz et al., 2013; Singer & Antrobus, 1963), experience sampling (Killingsworth & Gilbert, 2010; Song & Wang, 2012), and neuroscience methods (Christoff et al., 2016;

Fox et al., 2015) have provided valuable insights into what people generally tend to think about or the moment-to-moment dynamics of thought, but not at the same time. Think aloud methods (Ericsson & Simon, 1984) – where participants verbalize their stream of thought as it unfolds – are currently the most promising method for capturing the content and dynamics of spontaneous thought simultaneously (Raffaelli et al., 2021; Sripada & Taxali, 2020). However, the typical methods used to analyze think-aloud data entail labor-intensive manual coding schemes, making them impractical and expensive, particularly for large datasets. In this dissertation, we show how new techniques in natural language processing offer solutions for efficiently analyzing the dynamics of thought based on think-aloud data by using a sentence parser to split transcripts into thoughts and a hierarchical clustering algorithm to group thoughts into topics.

Analyzing a complex, unconstrained, and elusive phenomenon like spontaneous thought requires a multi-faceted approach. This dissertation used large-scale online datasets, traditional lab-based social psychology experiments, and archival analysis. We measured the content of thought in terms of episodic detail, pandemic-related content, and social content. This range of methods helped triangulate sometimes small effects to gain nuanced insights into the dynamics and contents of spontaneous thought.

Future applications of framework and analysis tools

The ideas and methods developed in Chapters 1 and 2 can be applied to study the consequences of spontaneous thought. For instance, many mental health disorders are characterized by altered patterns of spontaneous thought, including depression (Marchetti et al., 2016; Nolen-Hoeksema et al., 2008; Watkins, 2008), anxiety (Borkovec et al., 1998;

Marchetti et al., 2016; Spinhoven et al., 2015; Watkins, 2008), bipolar disorder (Marchetti et al., 2016), attention deficit disorder (Franklin et al., 2017; Shaw & Giambra, 1993), post-traumatic stress disorder (Brewin, 1998; Reynolds & Brewin, 1998), obsessive-compulsive disorder (Cole & Tubbs, 2021; Gehrt et al., 2020; Seli et al., 2017), etc. Common symptoms in these disorders related to spontaneous thought include rumination, racing thoughts, and intrusive thoughts.

The tools developed in Chapter 2 can help identify how thoughts go astray in these disorders. For instance, depression and anxiety are both associated with repetitive, negative, and less future-oriented thought (Giambra, 1974; Larsen & Cowan, 1988; Marchetti et al., 2016; Watkins, 2008). While these general features look similar between the two, we expect that the underlying patterns differ: depression may be characterized by "stickier" thoughts with fewer topic switches, whereas anxiety may be represented by faster thoughts that do switch but keep jumping back to a certain topic. We can quantify these features of thoughts using parameters determined by our automated analysis tools, such as the number of thoughts per topic, time spent per topic, and the average semantic distance spanned by topic jumps. By quantifying thought dynamics in this way, we can examine if symptoms like rumination are expressed differently in different mental health disorders and potentially use these metrics to more accurately distinguish how spontaneous thought goes awry.

In addition, we can use insights from the foraging model introduced in Chapter 2 to provide additional insight into the dynamics of thought in mental health disorders. Specifically, we can test if the patch switching threshold in the foraging model is linked to aberrant thought dynamics in specific conditions. For example, a threshold higher than optimal should produce more repetitive thought, like in depression and anxiety, whereas a lower

than optimal threshold should produce variable and disjointed thought patterns like those bipolar patients experience during mania. These analyses can yield valuable insights into the cognitive underpinnings of mental health disorders and can help develop more effective cognitive and psychiatric treatments.

Spontaneous thought has not only been linked to adverse mental health outcomes but can also have positive consequences like facilitating creativity and insight (Craig et al., 2018). The ability to generate creative ideas is associated with attributes of the dynamics of spontaneous thought, like the speed of thought (Kwiatkowski et al., 1999) and the structure of associations made during free thought (Kenett et al., 2014). Similar to the analyses of spontaneous thought in mental health proposed above, we can apply our methods to creative thought to gain insight into the specific dynamics of thought that give rise to optimal creative ideation. By comparing patterns of spontaneous thought in highly creative individuals to average individuals, we can identify the ingredients for creative thought.

Summary

Overall, the work presented in this dissertation provides a theoretical framework of spontaneous thought that can help generate hypotheses about the contents and dynamics of spontaneous thought based on insights from the memory literature. Combined with modern natural language processing techniques, this can offer powerful new insights into spontaneous thought. For instance, using insights from models of semantic fluency, we showed that the dynamics of spontaneous thought are optimized for memory consolidation and prioritizing current concerns. Analysis of the contents of spontaneous thought in social contexts shows similar effects: the external social world is reflected in spontaneous thought,

as are our most dire social needs. Spontaneous thought is a cornerstone of cognition and a powerful window into the human mind. The ideas and tools presented in this dissertation can help pave the way toward discoveries about the nature of spontaneous thought and its implications.

A

Supplemental Information for Chapter 3

Supplemental Information

We collected several measures for exploratory purposes that were not reported in the manuscript.

All data is available online on the Open Science Framework (https://osf.io/cew8b/), with

the exception of free response data that can contain personally identifiable information.

Study 3.1

Methods

During the mind wandering task, the text was displayed in chunks of 2-3 complete sentences (about 400-500 characters) to ensure it would fit on the screen in easy-to-read sections. The timing of the probes was determined by generating a random number of seconds between 120 and 240 for each probe. Participants advanced the text by pressing the space bar and could return to previous pages by pressing backspace. For the subjective measure of social thought, we excluded raters who had a standard deviation of 10 or less in all of their ratings. We set this criterium a priori to exclude raters who choose the same response every time. The effect of this rule was minimal, resulting in 8 exclusions out of 300 raters for Study 2 and no exclusions for Study 1 and Study 3.

Condition	Number of participants	Average number of trials per participant (SD)	Rate of self-reported mind wandering (SD)	Average number of characters (SD)	Average number of words (SD)
Solitude	36	10.89 (2.58)	0.33 (0.24)	122.4 (138.5)	22.7 (25.7)
Control	43	11.02 (2.65)	0.38 (0.25)	130.2 (115.1)	24.1 (21.0)

Table A.1: Mind wandering statistics for Study 3.1

Additional Results

Responses from the mind wandering task were not just rated on social content, but also on task-related content, memory-based simulation, introspection, and semantic information. There was a significant interaction effect between mind wandering and condition for the ratings of memory-based simulation ($\beta = -10.05, SE = 3.01, p < 0.001$), such that participants in the solitude condition showed fewer memory-based thoughts during mind wandering (Mind wandering $M_{control} = 47.18, SD_{control} = 25.26, M_{solitude} = 36.02, SD_{solitude} = 22.04$; No mind wandering $M_{control} = 27.74, SD_{control} = 17.59, M_{solitude} = 25.88, SD_{solitude} = 16.12$). The effect of solitude was limited to social thought and memory, as there were no significant interaction effects for the ratings of task-related content ($\beta = -.25, SE = 3.33, p = 0.94$), introspection ($\beta = 1.05, SE = 3.24, p = 0.75$), or semantic information ($\beta = -.30, SE = 2.33, p = 0.90$). In the fMRI analysis, we conducted exploratory analyses testing for an interaction between condition (isolated vs. control) and target (friend vs. Obama, and friend vs. self). The results support the social processing hypothesis: the difference in activation in the mentalizing network between the friend and Obama targets was larger for control participants than isolated participants ($M_{solitude} = -0.181, M_{control} = 0.286, t(78.561) = 3.63, p < 0.001$). The difference in activation for the friend and self target was also larger for control participants than isolated participants ($M_{solitude} = 0.544, M_{control} = 0.786, t(75.172) = 2.30, p = 0.024$)

Additional Measures

We included several measures for exploratory individual differences analyses were included in this study. All measures not discussed in the main text are listed below. Participants completed a survey approximately one week in advance of the study, hourly surveys at the start of the study and each hour for 6 hours, and an exit survey at the end of the study, after fMRI scanning.

Survey Data. The initial survey taken in advance of the study included some measures administered only once: the Big Five Inventory (John et al., 2008), Inclusion of Other in the Self task (Aron et al., 1992) using the name of the friend also used in the social inferences task during scanning, and questions on typical daily social life and social media use. The latter consisted of participants indicating how many hours per day on average they spent asleep, awake and alone, around other people but not interacting, and interacting with others, and how many times per day they sent texts/instant messages, emails, and checked social media. Other items in the initial survey were repeated in the exit survey at the conclusion of the study. These measures were the Rosenberg Self-Esteem scale (Rosenberg, 1979), Contingencies of Self-Worth Scale (Crocker et al., 2003), Daily Spiritual Experiences Scale (Underwood, 2006), Visual Perspective Taking (Zhao et al., 2015), Empathy Quotient (Baron-Cohen & Wheelwright, 2004), UCLA Loneliness scale (Russell, 1996),

Need to Belong scale (Leary et al., 2013), and Interpersonal Regulation Questionnaire (Williams et al., 2018). The exit survey also contained measures not included in the initial survey. These were the Valence-Arousal Emotional graph, Domain vs. Causal History task (Lombrozo & Carey, 2006), Patterns of Generalization (Lombrozo & Gwynne, 2014), Liking for ambiguous and unambiguous figures, Need for Closure – Ambiguity subscale (Webster & Kruglanski, 1994), Self-Ratings of Personality, Emodiversity (Quoidbach et al., 2014), Behavior Identification Form (Vallacher & Wegner, 1989), Anchoring and Adjustment Questionnaire, Category Learning (Williams & Lombrozo, 2010), Social Desirability (Crowne & Marlowe, 1960), Religious Orientation Scale (Allport & Ross, 1967), Body Consciousness Scale (Miller et al., 1981), and an anthropomorphism measure in which two abstract objects were presented and participants were asked to write a short story using those two objects. Participants completed 7 short surveys throughout the day, one at the start of the experiment (hour 0), and one at the end of every hour for the subsequent 6 hours. These surveys consisted of a free response prompt ("Please write down any comments, remarks, or notes.") and the Positive and Negative Affect Scale (PANAS; (Watson et al., 1988). At four timepoints – hours 0, 2, 4, and 6 – the survey also included an anthropomorphism measure. This consisted of three abstract objects, presented one-by-one, with the open-ended question: "What does this object look like?". For the control group, these surveys also included questions about what they did in the last hour. Control participants

where asked how much time in the last hour they had spent alone, around other people but not interacting, interacting with others in person, and asleep. They were also asked how many times in the past hour they texted or instant messaged someone, checked social media, or emailed someone, followed by an open ended item: "What did you do since the last survey?"

fMRI. In addition to the social inferences task reported in the manuscript, participants completed several other tasks during fMRI scanning. Participants first did the Attention Network Task (Fan et al., 2005). Then, in counterbalanced order, participants did either the social inferences task or a sharing task. In the sharing task, participants answered questions about themselves. The questions were preference statements, like in the social inferences task. On half the trials, the question appeared under the word PRIVATE, in the other half it appeared under the word SHARED. Participants were told that when the word SHARED was on the screen their responses would be shared with future participants and the experimenter in the next room, while PRIVATE trials would not be shared with anyone. Finally, participants completed a resting state scan.

Study 3.2

Condition	Number of participants	Average number of trials per participant (SD)	Rate of self-reported mind wandering (SD)	Average number of characters (SD)	Average number of words (SD)
Social presence	43	12.33 (1.22)	0.37 (0.26)	140.6 (102.3)	25.9 (19.1)
Control	42	12.52 (1.36)	0.40 (0.24)	147.7 (130.6)	27.3 (23.8)

Table A.2: Mind wandering statistics for Study 3.2

Additional Results

Since the parametric analysis method yielded null results, we ran a Bayesian version of the same models to assess evidence for the null hypothesis. To do this, we compared the model used in the main analysis, with a null model that did not include the interaction effect. This showed substantial evidence for the null model ($BF_{01} = 8.40$). As such, the Bayesian analyses support the findings from the parametric analyses: there is no effect of the social presence on spontaneous social thought. Responses from the mind wandering task were not just rated by mTurk participants on social content, but also on task-related content, memory-based simulation, introspection, and semantic information. The ratings of semantic information showed poor inter-rater reliability and were not analyzed for this study. Memory-based simulation shows a significant interaction effect ($\beta = -7.04, SE = 2.99, p = 0.02$; Mind wandering $M_{control} = 54.1, SD_{control} = 26.05, M_{social\ presence} =$

47.90, $SD_{social\ presence} = 24.77$; No mind wandering $M_{control} = 39.1, SD_{control} = 21.01, M_{social\ presence} = 39.37, SD_{social\ presence} = 20.7$), such that social presence decreased memory-based thought, contrary to expectations. Mere social presence did not affect task-related content ($\beta = -2.34, SE = 2.48, p = 0.35$), or introspection ($\beta = 2.01, SE = 2.77, p = 0.47$). The ratings of semantic information showed poor inter-rater reliability and were not analyzed for this study.

Additional Measures

In Study 2, participants completed a short survey after the mind wandering task including the UCLA loneliness scale, need to belong scale, and IRQ as described in Study 4. This survey also included the PANAS (Watson et al., 1988), and a moral word search task in which participants were asked to list the first five words they found in a word search containing both moral and non-moral words.

Study 3.3

Condition	Number of participants	Average number of trials per participant (SD)	Rate of self-reported mind wandering (SD)	Average number of characters (SD)	Average number of words (SD)
Social interaction	42	11.62 (1.32)	0.38 (0.24)	152.7 (122.8)	28.1 (23.4)
Control	40	12.00 (1.50)	0.42 (0.22)	161.9 (113.0)	29.4 (20.3)

Table A.3: Mind wandering statistics for Study 3.3

Additional Results

Responses from the mind wandering task were not just rated on social content, but also on task-related content, memory-based simulation, introspection, and semantic information. The effect of social interaction was limited to social thought, as there were no interaction effects for memory-based simulation ($\beta = -.40, SE = 2.66, p = 0.88$), introspection ($\beta = -2.04, SE = 2.93, p = 0.39$), or task-related content ($\beta = -2.92, SE = 2.74, p = 0.29$).

Additional Measures

In addition to the UCLA loneliness scale, need to belong scale, and IRQ discussed in Study 4, participants also completed the PANAS after the mind wandering task.

Study 3.4

Additional Analyses

To further unpack the results from Study 4, we correlated each social needs measure with social thought during mind wandering and social thought when not mind wandering. For each participant, we calculated the means of their objective and subjective social thought scores across all of trials where they reported mind wandering and across all trials where they reported not mind wandering. Since participants, on average, had more trials where they were not mind wandering than trials where they were mind wandering, the variance

for the estimates during mind wandering is higher (subjective social thought: $M_{\textit{no mind wandering}} = 14.68, SD_{\textit{no mind wandering}} = 6.97, M_{\textit{mind wandering}} = 16.62, SD_{\textit{mind wandering}} = 12.31$; objective social thought: $M_{\textit{no mind wandering}} = 4.51, SD_{\textit{no mind wandering}} = 3.17, M_{\textit{mind wandering}} = 3.99, SD_{\textit{mind wandering}} = 3.33$). Although there was no significant interaction effect for any of the survey variables with self-reported mind wandering, the relations between the survey measures and the objective measure of social thought are most prominent when participants are not mind wandering. The following correlations were all corrected for multiple comparisons using FDR correction. When analyzing only not-mind wandering trials, there is a negative correlation between objective social thought and loneliness ($r = -.21, n = 111, p = 0.03$), and positive correlations between objective social thought and need to belong ($r = .27, n = 123, p = 0.003$) and all four IRQ subscales (tendency-negative $r = .16, n = 123, p = 0.07$; tendency-positive $r = .22, n = 123, p = 0.02$; efficacy-negative $r = .15, n = 122, p = 0.11$; efficacy-positive $r = .15, n = 123, p = 0.09$). On trials where participants did report mind wandering, the IRQ subscales each show positive correlations with objective social thought as well (tendency-negative $r = .25, n = 118, p = 0.01$; tendency-positive $r = .18, n = 118, p = 0.05$; efficacy-negative $r = .22, n = 117, p = 0.02$; efficacy-positive $r = .22, n = 118, p = 0.02$). However, loneliness and need to belong are not significantly correlated with objective social thought during mind wandering (loneliness $r = -.11, n = 106, p = 0.27$; need to belong

$r = .1, n = 118, p = 0.3$). Additionally, participants who had higher loneliness scores reported mind wandering more frequently ($r = .29, n = 112, p = 0.008$).

Need to belong correlates at .5-.6 with the IRQ subscales. Loneliness does not significantly correlate with need to belong ($.16, p = .1$) or any of the IRQ subscales except efficacy-positive ($-.2, p = .03$).

	1. Social content overall (objective)	2. Social content during mind wandering (objective)	3. Social content - not mind wandering (objective)	4. Social content overall (subjective)	5. Social content during mind wandering (subjective)	6. Social content - not mind wandering (subjective)	7. Need to belong	8. Loneliness	9. IRQ (Tendency Negative)	10. IRQ (Tendency Positive)	11. IRQ (Efficacy Negative)	12. IRQ (Efficacy Positive)
2	0.56***											
3	0.81***	0.12										
4	0.11	0.12	0.02									
5	0.25**	0.41***	0.08	0.67***								
6	0.00	-0.13	0.11	0.77***	0.26**							
7	0.26**	0.10	0.27**	0.01	-0.08	0.04						
8	-0.22*	-0.11	-0.21*	-0.03	-0.07	-0.08	0.15					
9	0.25**	0.25**	0.16	0.03	-0.08	0.03	0.59***	-0.01				
10	0.31***	0.18	0.22*	-0.06	-0.05	-0.10	0.51***	-0.04	0.63***			
11	0.25**	0.22*	0.14	0.02	-0.08	-0.02	0.65***	-0.10	0.72***	0.66***		
12	0.25**	0.22*	0.15	-0.04	-0.02	-0.15	0.53***	-0.23*	0.56***	0.63***	0.59***	(23.8)

Table A.4: Correlations between all variables

Mini Meta-Analysis (Studies 3.1-3.3)

Methods

Since the first 3 studies all contained the same variables and analysis models, we combined the analyses into one model. Like the study specific models, this model included fixed effects for mind wandering, condition, and the interaction between mind wandering and condition. The model also contained random intercepts for participant and study.

Results

In line with the results from the individual models, there were significant interaction effects between mind wandering and condition. The interaction between mind wandering and being in the solitude condition was negative (subjective measure: $\beta = -4.89, SE = 2.00, p = 0.01$; objective measure: $\beta = -3.16, SE = 0.71, p < 0.001$), while the interaction between mind wandering and being in the social interaction condition was positive (subjective measure: $\beta = 6.07, SE = 1.72, p < 0.001$; objective measure: $\beta = 3.52, SE = 0.64, p < 0.001$). There were no significant interaction effects between mind wandering and being in the social presence condition (subjective measure: $\beta = 0.17, SE = 1.70, p = 0.92$; objective measure: $\beta = 0.90, SE = 0.62, p = 0.15$).

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