THE REPETITION DECREMENT EFFECT

THE REPETITION DECREMENT EFFECT:
A DIRECT MEASURE OF ENCODING COSTS ATTRIBUTABLE TO PRIOR EXPERIENCE

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A Thesis Submitted to the School of Graduate Studies in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy

McMaster University

Descriptive Note

DOCTOR OF PHILOSOPHY (2018) McMaster University (Psychology)

TITLE: The Repetition Decrement Effect: A Direct Measure of Encoding Costs Attributable to Prior Experience

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NUMBER OF PAGES: xviii, 195

Lay Abstract

The brain is the single most energy demanding organ in the human body. Consequently, evolution ought to have produce adaptations that minimise redundant brain activity. One way to minimise redundant brain activity is to avoid re-learning what has already been learned. Counter-intuitively, this idea implies that we learn more when we know less and learn less when we know more. The present thesis focuses on a phenomenon I call the repetition decrement effect – poor memory for a word studied twice relative to a word studied once. This effect occurred when: (1) the first presentation of the word was ignored, and (2) the repetition of the word was immediate. These characteristics link the repetition decrement effect to the classic spacing effect and support the theory that our brain attempts to minimise energy expenditure related to the learning of redundant information.

Abstract

The brain is the single most expensive organ in the human body (Berg, Tymoczko, & Stryer, 2002). Given that energy is scarce, evolutionary pressures ought to promote the development of cognitive systems that efficiently attend to and learn our environment (Christie & Schrater, 2015). One way of achieving efficiency involves reducing the amount of resources we devote to information that is already well-learned. Although the idea that attention is biased against redundancy is well supported (Posner & Cohen, 1984; Tipper, 1985), evidence for a similar bias in learning and memory is less clear. The classic spacing effect (Ebbinghaus, 1885) does imply that immediate repetitions triggers 'deficient processing' and poor memory relative to spaced repetitions (Hintzman, 1976). However, the link between the spacing effect and deficient processing relies on indirect inference. In this thesis, I propose that the repetition decrement effect (Rosner, López-Benítez, D'Angelo, Thomson, & Milliken, 2018) is a direct measure of deficient processing. The repetition decrement effect is a recognition memory deficit for words presented twice at study relative to words presented only once. In this thesis, this effect occurred when: (1) the first presentation of two identical words was poorly processed, and (2) the second presentation of two identical words followed immediately after the first. When repetitions were spaced, repetition always improved recognition. The interaction between repetition and spacing provides evidence that the repetition decrement effect is driven by the same 'deficient processing' mechanism that underlies the spacing effect. An instance model of memory (based on Minerva-AL; Jamieson, Crump, and Hannah, 2012) that mathematically formalises this deficient processing mechanism successfully predicted both the repetition decrement and spacing effects. The repetition decrement effect represents the strongest evidence to date that, like attention, learning mechanisms are mediated by an adaptive system that biases against the processing of redundant information.

Acknowledgements

The thesis presented here is the culmination of twenty-four years of formal education and countless hours of informal education besides. It would be foolhardy to attempt to exhaustively thank everyone who has instructed, inspired, or influenced me through this process. Rather, I will do my best to thank those who have directly influenced me during the final stretch of this long journey.

I must first begin by thanking my supervisor, Bruce Milliken. You have been an exceptional mentor over these four years. I consider myself extremely lucky that your eyes fell upon my application to McMaster. I cannot imagine a reality where this did not happen. Your passion for research has and continues to inspire me to do good science. Thank you for recruiting me into your team and supporting me. I could not have done this without you.

I next thank my co-authors. To Tamara Rosner: You were the first student at McMaster I ever met. You welcomed me and provided crucial early support with experimental design and programming. This support was instrumental in undertaking my research program started. Without you, I would have been lucky to accomplish half of what I did. To Randy Jamieson: although my time at the University of Manitoba was short, your tutelage was transformative. You have greatly influenced my philosophy of and approach to experimental psychology and introduced me to the wonderful world of modelling.

To my committee members Judith Shedden and Scott Walker. Judith, you were the first professor I worked for at McMaster University. You were a

wonderful boss and an excellent indicator that I had indeed made the right choice in attending McMaster. In your role as my committee member, you have provided much guidance and support as I expanded the scope of my academic interests. Scott, I admire your passion for research and your breadth of knowledge. Through the weekly reading groups and your role as my committee member, you have helped to expand the scope of my knowledge by an order of magnitude. Thank you both.

To the Milliken lab, thanks for cultivating my curiosity and providing the sort of feedback and support critical to person's development as a scientist. You have all contributed to an exceptionally welcoming and productive environment. To Mitch and Ellen, my fellow east coast Canadians: You were both amazing companions and supportive peers. I will fondly remember the shed parties, the poker nights, and our adventures and escapades during conferences. To Brett, I have very much enjoyed our long conversations on a myriad of topics ranging from culture and politics to philosophy and science. Our talks were meandering and frequently lasted many hours, but they were always enjoyable. To David, thank you for your humour, your lab contributions, and the loan of your Commodore-64; it was instrumental in some of my music projects. To Hanae, Lisa, Andrew, Brenden, Amy, Connie, Chao, and anyone else I may have missed, thank you for providing a wonderful lab environment conducive to academic and professional growth. Your contributions were always on point.

To Sarah, my fiancé. We met shortly after the beginning of my post-secondary career, and there is no one more intimately familiar with my journey. As we both approach the end to our respective educational paths, I must reflect on all that we have done to encourage and support each other. There were many times when the completion of either of our educational journeys seemed far from certain, but we persevered nonetheless. I look forward to beginning the next stage of our lives together. I cannot imagine spending it with anyone else. I love you.

To my grandparents, Fred and Hannah Collins and Bob and Fran Brown, each of you has supported me in ways I could never fully express. Thank you for everything you have done as role models and supporters of my education.

And finally, to my parents, Ivan and Mary: Everything began with the two of you. You have both encouraged my curiosity in the world unfailingly. You worked hard to ensure I had every opportunity and tool necessary to satiate that curiosity. You never discouraged any of my interests or pursuits, no matter how fleeting or silly they may have been. You took them seriously because you took me seriously. It is for that reason that I have become the scientist- and indeed person- that I am today. I could never hope to repay my debt to either of you. I was raised in a small town, but you gave me the world. Thank you for believing in me; I love you both.

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Declaration of Academic Achievement

This is a 'sandwich' thesis. The first empirical chapter (Chapter 2) has been published in a peer-reviewed journal. The second empirical chapter (Chapter 3) has been submitted to a peer-reviewed journal for review. The third empirical chapter (Chapter 4) is intended for submission to a special issue. I am the first author for each of these empirical chapters. Other co-authors include a McMaster colleague on the first manuscript, an external collaborator on the third manuscript, and my supervisor on all three manuscripts. The remainder of the preface is intended to clarify my contributions to the manuscripts that comprise the empirical chapters of this thesis.

The first empirical chapter is a reprint of Collins, R. N., Rosner, T. M., & Milliken, B. (2018). Remembering 'primed' words: The effect of prime encoding demands. *Canadian Journal of Experimental Psychology/Revue Canadienne de Psychologie Expérimentale, 72*(1), 9–23. I was the primary writer on this manuscript. I performed all data analysis and contributed to the programming, data collection, and experimental design.

The second empirical chapter is the manuscript Collins, R. N., & Milliken, B. (under review). The repetition decrement and spacing effects: Evidence for the deficient processing of primed words. *Acta Psychologica (*Manuscript ID: ACTPSY_2018_299). I was the primary author on this manuscript as well. I programmed the experiment and performed all data analysis, along with contributing to data collection and experimental design.

The third empirical chapter is the manuscript Collins, R. N., Milliken, B., & Jamieson, R. K. (in prep). An instance model of the repetition decrement and spacing effects. The manuscript has not yet been submitted because it is intended for submission as part of a special issue of the *Journal of Memory and Language*, with submissions opening on the 1st of October 2018. I was the primary author on this manuscript. I designed and programmed the experiment, and further collected and analysed the data. I also contributed to the design and programming of the memory model.

CHAPTER 1 – Introduction

Cognition is expensive. Humans' ability to learn, retain, and synthesise information confers a great survival advantage but comes with a significant cost. The brain is the single most energy-intensive organ in the human body, accounting for just 2% of total body mass but 20% of our basic metabolic energy expenditure (Berg, Tymoczko, & Stryer, 2002; Raichle & Gusnard, 2002; Pellerin & Magistretti, 2003). The expense of mental processes results in immense evolutionary pressure driving the development of efficient systems that attend to and encode information important to survival and reproduction (Christie & Schrater, 2015). Consequently, attention to and encoding of redundant information must be minimised.

What types of processes are needed to reduce the redundant encoding of information that is already well-represented in memory? The key process would have to be an "inexpensive", fast evaluation of what information is redundant, and therefore ought not to be re-encoded in memory. From this perspective, some form of early and automatic assessment of redundancy must play an important role in mediating the attention and memory systems. This early and automatic assessment of redundancy can be thought of as a heuristic aimed at adaptive and efficient learning. As with most heuristics, it operates quickly, but imperfectly. Evolution is, after all, guided by the principle of 'good enough' rather than 'perfect' (Gould & Lewontin, 1979). The goal of this thesis is to present a set of empirical results and theoretical ideas that are centred on a heuristic of this type, and that I propose mediates the interaction between attention and memory encoding.

To provide context for the studies in this thesis, in this introduction I will first provide a brief overview of the distinction between implicit and explicit memory (Graf & Schacter, 1985), and how the redundant encoding issue described above impacts each of these forms of memory. Second, I will discuss what I call the “repetition paradox”. In short, the domain of attention and performance is rife with examples of stimulus repetition impairing performance (Milliken, Thomson, Bleile, MacLellan, & Giammarco, 2012; Posner & Cohen, 1984), whereas the domain of memory consists primarily of examples of stimulus repetition facilitating performance (Bodner & Masson, 1997; Ebbinghaus, 1885; Graf & Mandler, 1984). Importantly, although the beneficial effects of repetition on learning and memory are well represented in the literature, there is also an emphasis in the same literature on the deficient processing of repeated stimuli spaced close together in time. These inferences are derived indirectly from findings of the spacing effect (Hintzman, 1974; Mammarella, Russo, & Avons, 2002). In the third section, I describe the repetition decrement effect (Rosner, López-Benítez, D’Angelo, Thomson, & Milliken, 2018), which is the focus of the empirical and modelling work presented in this thesis. This effect demonstrates that recognition for the same word seen twice in immediate succession can be worse than for a word seen just once, it highlights the idea that attention processes favour memory encoding for novel over familiar events, and it may provide a direct measure of deficient encoding thought to contribute to the spacing effect.

Multiple Systems, Processing, and Redundant Encoding

Memory involves the encoding, storage, and retrieval of our interactions with information in the world around us. The mental processes that comprise memory allow us to apply knowledge from experience to future tasks. It is fundamental to every attribute we associate with being human: Learning, language, relationships, and even our sense of personal identity (Eysenck, 2012). A key issue in the field of human memory is whether it ought to be conceptualised as a unitary system or broken down into separate systems. Much research over the past four decades has highlighted a difference between explicit and implicit memory (Graf & Schacter, 1985), which has also supported a distinction between declarative and non-declarative memory systems (Squire, 2009).

Explicit memory refers to deliberate attempts to retrieve a specific prior experience. When successful, it produces a sense of conscious awareness of the past (Graf & Schacter, 1985). One example of an explicit memory test is free recall, where participants are asked simply to remember as much as they can from an earlier study phase without any additional cues. Another example of an explicit memory test is recognition, where participants make forced-choice old/new decisions in response to a mixture of previously studied and unstudied stimuli (Atkinson & Juola, 1974; Tulving, Schacter, & Stark, 1982). Ideally, "old" responses are made to stimuli that were presented in the study phase, and "new" responses are made to stimuli that were not presented in the study phase. Performance is measured in terms of *hits* ("old" responses to "old" items) and *false alarms* ("old" responses to "new" items). Tests of explicit memory have in common that they provide a direct measure of participants' ability to access information stored in memory. In this respect, explicit memory tests treat memory as an object (Jacoby & Kelley, 1987), something that is attended to by the participant to complete the task at hand.

How might explicit memory be affected by mechanisms that reduce the encoding of redundant information, as discussed at the outset of the Introduction? Consider that there is often much overlap between day-to-day life experience and past experience. If the encoding of redundant information is to be minimised, the implication is that a substantial amount of our day-to-day experience will be subject to diminished encoding. This neglect to encode all aspects of all experiences must compromise explicit memory in some way. How are we able to retrieve specific episodes from memory efficiently in light of mechanisms that limit the encoding of redundant information?

As it turns out, the subjective sense that we re-activate prior experiences in all their specific detail is likely to be illusory. Consider the example of remembering this morning's commute to work. You may have the subjective experience of remembering the commute in substantial detail, but it is likely that much of the remembering is supported not solely by this morning's experience, but also by many similar experiences of having made the same commute. In the absence of a distinct event (Einstein & Hunt, 1980; Hunt & Einstein, 1981), even fewer details are likely to be remembered about a commute from a week ago, and fewer still about a commute from a month ago. In all of these cases, what is likely to be retrieved is a representation that combines distinct details of the probed episode together with other knowledge from many similar episodes that ‘fill in the gaps’ (Burgess, 1996). This notion of memory retrieval emphasises its reconstructive nature (Bartlett, 1932; see also Schacter, 1989), and is a logical consequence of a mind that minimises the encoding of redundant information.

In contrast to explicit memory, implicit memory concerns influences of memory on performance that are not triggered by a deliberate attempt to remember. Instead, implicit memory is thought to occur when one or more prior experiences influence performance on a non-remembering task, typically without awareness of the relation between the prior experience(s) and current performance. One example of an implicit memory effect is known as ‘priming’, where performance is influenced by pre-exposure to matching or similar stimuli (Tulving et al., 1982; Tulving & Schater, 1990). For example, Jacoby and Dallas (1981) demonstrated that prior exposure to a set of words increased the likelihood that those same words could be identified in a later perceptual identification task. Note that the goal of the perceptual identification task was to identify briefly presented and masked words, not to remember those words. Tests of implicit memory have in common the use of indirect measures; that is, measures that aim at some aspect of performance other than memory. In this respect, implicit memory can be thought of as a tool rather than an object (Jacoby & Kelley, 1987), something that we use to accomplish a goal other than remembering.

How might implicit memory be affected by mechanisms that reduce the encoding of redundant information? The concept of implicit memory fits with the idea that many of our everyday interactions with the world involve very little new learning, and instead involve the retrieval of old learning. In this sense, reduced encoding of redundant information does not pose a constraint on implicit memory as it does for explicit memory. Rather, reduced encoding of redundant information offers another lens for understanding implicit memory – the limited processing resources required for learning are spared in many everyday contexts by automatically retrieving similar representations stored in memory. In this way, memory is used without intention and reduces the need for learning.

Support for the distinction between implicit and explicit memory comes from multiple lines of research. Behaviourally, task performance dissociations in healthy adults are often observed. Jacoby and Dallas (1981) showed one such dissociation when they asked participants questions about words in a study list. The questions required either shallow encoding (e.g., was a letter present in a word) or deep encoding (e.g., a question about the meaning of the word). Depth of encoding affected performance on a recognition test, an explicit memory test, but had a negligible effect on a perceptual identification task, an implicit memory test. Additional evidence comes from studies of aging (Gabrieli, Fleischman, Keane, Reminger, & Morrell, 1995; Isingrini, Vazou, & Leroy, 1995), and amnesic populations (Graf & Schacter, 1985; L. L. Jacoby & Witherspoon, 1982), where participants exhibit selective performance impairment on explicit memory but not implicit memory tasks.

Although the distinction between explicit and implicit memory has received wide acceptance, an alternative framework for interpreting human memory is the "processing view". According to this view, all memory is stored episodically in a single system. Different memory phenomena arise not from those memories being stored in different systems, but from differences in the way memories are retrieved from a single system (Blaxton, 1989; D. L. Hintzman, 1984, 1986; Whittlesea & Dorken, 1993). For example, implicit memory phenomena may arise from the joint retrieval of a set of related episodes, whereas explicit memory phenomena may arise from the specific retrieval of a single episode (D'Angelo, 2013). The multiple trace model of memory known as MINERVA-2 is built on a formalised expression of these assumptions (Hintzman, 1984, 1986) and predicts many phenomena that otherwise might be attributed to separate memory systems.

As noted above, the processing view of memory depends on variations in how memory is retrieved, in combination with how those memories were encoded, to explain how memory performance varies as a function of task and context. The transfer appropriate processing principle describes this dependence; memory performance varies as a function of how well the processes engaged in at the time of retrieval match those engaged in at the time of study (Blaxton, 1989; Morris, Bransford, & Franks, 1977). This principle appears to hold well both for memory that is accompanied by awareness (Blaxton, 1989; Higham & Vokey, 1994; Whittlesea, 2002; Whittlesea, Dorken, & Podrouzek, 1995) and memory influences that are unaccompanied by awareness of prior experience (Hommel, 1998b; Logan, 1988). How does the transfer appropriate processing principle fit with the idea that encoding of redundant information must be minimised? Minimizing the encoding of redundant information implies that similar experiences likely share parts of their representations. It seems reasonable that distinctive aspects of task and context would serve as important cues to tease apart these similar representations, an idea that is well-captured by the transfer appropriate processing principle.

The Repetition Paradox

Stimulus repetition can have different effects on performance in different empirical domains. I focus here on the apparently different effects of stimulus repetition in the domains of attention and performance on the one hand, and human memory on the other hand. In the attention and performance domain, several well-known phenomena point to stimulus repetition impairing perceptual encoding, perhaps because attention is biased toward novelty rather than familiarity (Posner & Cohen, 1984; Yantis & Jonides, 1984). In contrast, in the human memory domain, stimulus repetition generally improves performance on both implicit (Balota & Spieler, 1999; Bodner & Masson, 1997; Erickson &

Reder, 1998) and explicit tasks (Ebbinghaus, 1885; Kynette, Kemper, Norman, & Cheung, 1990). Without a coherent theory of attention, learning, and memory that accounts for these different effects they can appear paradoxical.

Stimulus Repetition in the Attention and Performance Domain

Imagine you are an early human hunter-gatherer keeping watch for your tribe at night. Something in your visual field moves strangely, grabbing your attention. You intently focus on this strange motion only to realise it is a shadow cast by a fire. Your continuing success at this job now requires you to disengage from this old, irrelevant location and look for threats elsewhere. This ability to disengage and attend elsewhere broadly points to ‘foraging’ as a critical component of visual search (Wolfe, 2013), and speaks to a need to deploy attentional resources efficiently. In the domain of attention and performance, the phenomenon known as inhibition of return (IOR) is thought to capture a fundamental process akin to foraging that underlies visual search.

IOR is an attentional orienting effect that appears to reflect a bias against attending to previously attended locations (Posner & Cohen, 1984). A typical IOR experiment presents participants with an abrupt onset cue in one of two marked peripheral locations left and right of fixation. A target then appears at either location and participants are required to detect its onset, or in some cases to perform a perceptual discrimination task. Notably, response times for targets that appear at the same location as the cue are slower than for targets that appear at the location opposite the cue when the delay between the cue and target onset exceeds about half a second. Posner and Cohen (1984) suggested the effect could be due to a nonspecific impairment of encoding efficiency related to cueing, but that it could also reflect a bias favouring shifts of attention to novel locations rather than to locations that have been previously attended. Similarly, Klein (2000) argued that attentional disengagement from the cued location leads to a delayed response to following targets at that location because attention is inhibited from reorienting to the previously attended location. Regardless of the precise theoretical account, the IOR effect constitutes an example of more efficient perceptual encoding of targets that mismatch prior cues (or primes) than for targets that match prior cues (or primes). In this case, stimulus repetition leads to a cost in performance relative to stimulus alternation.

Although the vast majority of IOR studies have used spatial orienting procedures, a small number of studies have demonstrated non-spatial variants of the IOR effect. Law, Pratt and Abrams (1995) first demonstrated a non-spatial IOR effect with colour stimuli. Participants were asked to detect the onset of a target square that was either red or blue. The target was preceded either by a valid cue (a cue that matched the target colour) or an invalid cue (a cue that mismatched the target colour). Participants were significantly slower to respond to valid cue trials than to invalid cue trials, a colour based IOR effect. Similar effects have since been reported for discrimination rather than detection tasks and for a variety of non-spatial stimulus attributes (Francis & Milliken, 2003; Hu, Samuel, & Chan, 2011). In addition, such effects have also been observed in standard two-alternative forced choice tasks that require a discrimination response to both of two consecutive items, but only if an intervening event was presented and responded-to between consecutive targets (Spadaro, He, & Milliken, 2012; Spadaro & Milliken, 2013). These results offer demonstrations that stimulus repetition in the attention and performance domain can result in impaired perceptual encoding in the service of relatively simple detection and discrimination tasks. These results are generally consistent with the idea that attentive perceptual encoding is more robust for targets that mismatch immediately preceding items than for targets that match immediately preceding items. More broadly, these effects square well with ideas about redundant encoding discussed above, that the mind minimises energy expenditure by biasing attention against orienting to redundant events and instead favouring orienting to relatively novel events.

Although IOR is a particularly good example of an effect in the attention and performance domain that illustrates a stimulus repetition cost, there are others. For example, it is well documented in visual search research that attention shifts preferentially to new objects in search displays (Yantis & Jonides, 1984). In studies of ‘repetition blindness’, identification of rapid serial visual presentation (RSVP) targets is particularly poor for repeated items (Kanwisher, 1987). Finally, in studies of negative priming, identification and localisation responses are slow when targets match items that have been seen just previously as distractors. Although this effect was initially conceptualised as a form of short-term transient inhibition associated with resolving distractor interference, this view has been challenged by many observations of negative priming in tasks with single prime items that are presented on their own, rather than as distractors in a selective attention task (Milliken, Joordens, Merikle & Seiffert, 1998; Milliken, Lupianez, Debner & Abello, 1999; D'Angelo & Milliken, 2012). These results are more consistent with a view in which negative priming results from mechanisms like those that produce IOR effects (see Milliken, Tipper, Houghton & Lupianez, 2000; D'Angelo, Thomson, Tipper & Milliken, 2016). All told, these effects highlight the idea that attention orients with preference to new events rather then to events that are redundant with those already encoded, and that this attention orienting principle is consistent with the idea that encoding of redundant information is minimised.

Stimulus Repetition in the Human Memory Domain

We are all familiar with the idiom 'practice makes perfect'. That repetition enhances memory has been universally noted by ancient philosophers, early psychologists (Ebbinghaus, 1885), and contemporary scientists alike (Kuhl & Anderson, 2011; Mulligan & Peterson, 2013). In contrast to the attention and performance domain, it seems clear that stimulus repetition benefits human memory in many task contexts (Ebbinghaus, 1885; Greene, 1989; Hintzman, 1984; Kynette et al., 1990).

Implicit memory effects are a commonly observed result of stimulus repetition (Graf & Mandler, 1984). For example, repetition priming captures the enhanced accessibility of items recently encountered in tasks such as lexical decision (Balota & Spieler, 1999; Bodner & Masson, 1997; Meyer & Schvaneveldt, 1971) and word fragment completion (Erickson & Reder, 1998). As noted above, Jacoby and Dallas (1981) also reported that stimulus repetition improved perceptual identification.

Stimulus repetition also benefits performance in tests of explicit memory. Repeated study boosts performance on recognition tests (Glenberg, Smith, & Green, 1977; Greene, 1989; D. L. Hintzman, 1974, 1976; Woodward & Bjork, 1973) and recall tests (Ebbinghaus, 1885; Eichenbaum, 2001; Kynette et al., 1990) across many different classes of stimuli. Repetition also improves performance on stem-cued recall tests (Greene, 1986).

Although repeated study is associated with improved memory, this effect is hardly straightforward. Prolonged study often results in little to no benefits in tests of free recall (Greene, 1987). Furthermore, participants often fail to report repeated presentations of an item within a rapidly presented study list (Kanwisher, 1987). For other forms of explicit memory, there are usually diminishing returns (Challis & Sidhu, 1993; English & Visser, 2014), with increased study leading to increasingly smaller improvements in memory performance. The severity of diminishing returns appears to be related to the interval between repeated study events (Cuddy & Jacoby, 1982; Ebbinghaus, 1885; Murre & Dros, 2015), with longer spacing between repeated study events leading to larger improvements in memory performance and therefore a smaller diminishing returns effect. This benefit of increased time between repeated encoding on memory performance is known as the spacing effect.

The spacing effect is the ubiquitous observation that explicit memory improves more when there is a delay between repeated study events than when repetition occurs immediately (Ebbinghaus, 1885). The spacing effect is observed in both free recall and tests in which participants are provided with a retrieval cue (Greene, 1989). It occurs with many types of stimuli, including words (Challis, 1993; Ebbinghaus, 1885), faces (Mammarella et al., 2002), and pictures (Toppino & Bloom, 2002; Toppino, Kasserman, & Mracek, 1991). The literature on the spacing effect is extraordinarily rich. Of particular interest here is that mainstream theories of the spacing effect emphasise the diminished encoding of redundant information (Hintzman, 1976; Russo, Mammarella, & Avons, 2002).

This inference about the link between diminished encoding and the spacing effect is somewhat indirect. The inference that is directly supported by the spacing effect is that encoding is diminished for immediately repeated items relative to spaced repeated items. However, encoding of both immediate and spaced repetitions could benefit from repetition relative to an item encoded for the first time. In other words, the inference that is not directly supported by the spacing effect is that encoding is diminished for immediately repeated items relative to items encountered just once. From this perspective, the diminished encoding of repetitions would be strongly and directly supported not by spacing effects, but by worse memory performance for repeated items than an item encoded just once.

This type of direct observation of poor memory due to stimulus repetition is rare but has been reported in a small number of studies. In one recent study, Peterson and Mulligan (2012; see also Mulligan & Peterson, 2013) discovered that participants who studied a group of cue-target pairs twice recalled fewer targets on a later cued-recall test than did participants who studied the cue-target pairs only once. The effect occurred when participants were first presented the cue-target pairs in a disorganised list and later restudied as part of a semantically organised list. They called this observation the negative repetition effect. The negative repetition effect generalised to multiple encoding conditions and occurred with both free and cued recall tests. The researchers suggested the negative repetition effect occurred because the first presentation orients focus to the within-pair relationship, impairing the processing of between pair organisation that participants capitalised on when items were presented once.

Another example of poor memory due to stimulus repetition is the massed-repetition decrement effect (Kuhl & Anderson, 2011). This effect was observed in an experiment with a study phase in which participants repeated words (e.g. “sheep”) aloud one at a time for 0, 5, 10, 20, or 40 s. Note that words repeated for 0 s refers simply to words that have only been read aloud once. The test phase was a word association task consisting of a word followed by a single letter. The word and letter probe were designed to evoke a word from the study phase (e.g., “herd s____”; with an expected response of “sheep”) or a close associate (e.g., “fabric w____”; with an expected response of “wool”). Participants responded with the first word that came to mind, and performance was measured as a proportion of items for which participants gave the intended word response. Kuhl and Anderson (2011) found that words repeated for a brief period (5-10 s) produced beneficial priming effects for both repeated words and their semantic associates. This pattern reversed with a longer duration of repetition (20-40 s). Prolonged repetition did not drive free association performance below the baseline of not-repeated words though, suggesting repetition still broadly benefited memory. Regardless, the researchers suggested the effect was due to inhibition of semantic representations of repeated words, and that this inhibition spread to semantic associates. Specifically, the attentional focus on the phonological features – due to repeated naming – may weaken the semantic encoding that supports production of those items on a free association task.

It is important to note that both Mulligan and Peterson (2012, 2013) and Kuhl and Anderson (2011) attributed their effects to a reduction in inter-item relational encoding rather than item-specific encoding. As such, despite theories of the spacing effect making reference to diminished item-specific encoding (Hintzman, 1976; Russo et al., 2002) as a function of repetition, there is little direct evidence for such a process.

The Repetition Decrement Effect

There are good reasons to think that the encoding of redundant information should be minimised, which implies that stimulus repetition ought to have detrimental effects on stimulus encoding. Several findings from the attention and performance domain are consistent with this view, but to date there is little direct evidence for this finding in the human memory literature. Although the spacing effect suggests that immediately repeated information is subject to poor encoding (Bjork & Bjork, 1992; Hintzman, 1976), this is necessarily an indirect inference. If repeated stimuli are subject to encoding costs, then poorer explicit memory for repeated than for not-repeated items ought to be observable in tests that rely primarily on item-specific encoding, such as recognition (Hunt & Einstein, 1981). The repetition decrement effect is a missing piece of the puzzle and is the primary empirical focus of this thesis.

In the original repetition decrement effect procedure depicted in Figure 1 (Rosner, López-Benítez, D’Angelo, Thomson, & Milliken, 2018), participants were presented with a list of prime-target pairs consisting of a green prime word followed by a red target word. On half of the trials, the green and red words were the same (repeated trials); on the other half, the green and red words were different (not-repeated trials). The repeated trials and not-repeated trials were randomly intermixed. Participants were asked to name the red target words aloud but were given no instructions for the green prime word.

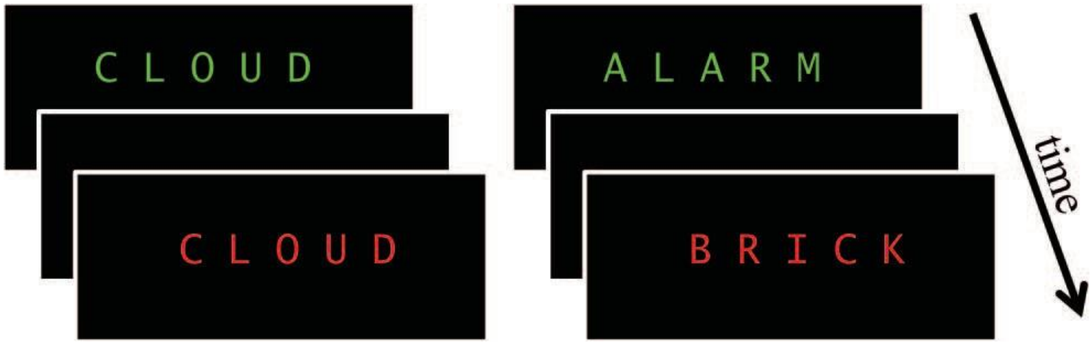

Figure 1. Examples of study phase items from Rosner et al. (2018), reproduced with permission.

Upon completing a 10-minute math distractor task, participants completed a surprise old-new recognition memory test. Recognition was better for not-repeated targets than for repeated targets – the repetition decrement effect. This effect persisted when a second, unrelated green prime was placed temporally between the prime and target, but disappeared when participants were explicitly instructed to attend to and name the green prime words aloud (Rosner et al., 2018). Unlike the negative repetition effect, this observation of poor memory for repeated information did not require semantically organised stimuli nor did it appear to result from inter-item relational encoding (Mulligan & Peterson, 2012, 2013). Instead, it constitutes a deficit in the item-specific processing of repeated targets. Furthermore, the repetition decrement effect used an incidental learning procedure, suggesting the effect did not result from voluntary metacognitive processes (Benjamin et al., 1998; Greene, 1989). Thus, the repetition decrement effect represents the first direct demonstration of poor explicit memory attributable to automatic item-specific encoding deficiencies for repeated stimuli.

In this thesis, I advance three major claims. First, the repetition decrement effect occurs because the ignored prime produces a false sense of the stimuli being well encoded, leading to poor encoding of the repeated target. Second, I propose the repetition decrement effect reflects the deficient processing mechanism theorised to produce the spacing effect (Bjork & Bjork, 1992; Greene, 1989; Hintzman, 1976) and is, therefore, a short-term effect. Finally, I propose that the process that underlies both the spacing effect and the repetition decrement effect is strongly automatic and involuntary. These three proposals are explored in the following empirical chapters.

Overview of the Empirical Chapters

Although the negative effects of repetition on attention have been well documented in the literature (e.g., Posner & Cohen, 1984), there are far fewer demonstrations of negative effects of repetition on memory. The repetition decrement effect is one such effect. This effect is a powerful tool for reconciling the contradictory effects of repetition on attention and memory. In Chapter 2 I examine boundary conditions of the repetition decrement effect by varying prime encoding. In Chapter 3, I develop a more robust account of the attentional and encoding mechanisms that produce the repetition decrement effect by examining its interaction with the spacing of repetitions. In Chapter 4, the final empirical chapter, I present a mathematical model of the repetition decrement effect and test the model's ability to predict results of a novel experimental design. Note that these empirical chapters are 'stand-alone' manuscripts intended for individual publishing. Consequently, there is some overlap in the introductions, methodological descriptions, and theoretical discussions found in each study. Despite the overlap, each manuscript presents unique experiments designed to address distinct theoretical questions united by the common theoretical framework of the thesis. Regardless, following the empirical chapters, I argue the results from the present work suggest the existence of a strongly automatic, involuntary system that drives the selection and encoding of information.

CHAPTER 2 – Remembering 'Primed' Words:
The Effect of Prime Encoding Demands

Collins, R. N., Rosner, T. M., Milliken, B. (2018).

Canadian Journal of Experimental Psychology, 72, 9-23

Preface

Chapter 2 presents the results of three experiments in which we explore the effect of prime encoding demands on the repetition decrement effect (i.e., better recognition for not-repeated target words than for repeated target words; Rosner et al., 2018). In Experiment 1, we found repetition decrement effects both in a condition that required passive ignoring of the prime (a simple replication) and in a condition that required active ignoring of the prime (a divided attention task). In Experiments 2 and 3 we manipulated the depth of prime processing across groups. When the prime encoding task was shallow (e.g., ignore the prime or count the vowels), we observed poor prime memory and a repetition decrement effect. When the prime encoding task was intermediate (e.g., naming the prime), we observed better prime memory and slightly better memory for repeated than not-repeated targets. Finally, when the prime encoding task was deep (e.g., answering a semantic discrimination question), we observed good memory for primes and superior memory for repeated targets. Importantly, this chapter shows that the processes driving the repetition decrement effect may always be active during the encoding of repeated targets, but that robust prime encoding can compensate for deficient processing.

Abstract

Rosner, Lopez-Benitez, D’Angelo, Thomson, and Milliken (2017) reported a novel recognition memory effect using an immediate repetition method during the study phase. During each trial of an incidental study phase, participants named a target word that followed a prime word that had the same identity (repeated trials) or a different identity (not-repeated trials). Recognition in the following test phase was better for the not-repeated trials. In the present study, we examined the influence of prime encoding demands on this counter-intuitive effect. In Experiment 1, we instructed one group to simply ignore the prime, as in the original study. A second group completed a divided attention task on prime presentation. Recognition memory was better for not-repeated than repeated words in both groups. In Experiment 2, encoding of the prime varied across three groups: one group named each prime, a second group counted the vowels in each prime, and a third group made a semantic discrimination for each prime. Recognition was better for repeated than for not-repeated words in the semantic group and did not differ across conditions for the other two groups. Finally, in Experiment 3, we assessed memory for not-repeated primes in addition to memory for targets (as in Experiments 1 and 2). The results confirmed that poor memory for the primes plays a significant role in producing the previously described effects. The results are discussed in relation to transient processing adaptations that affect memory encoding.

Introduction

Increases in processing difficulty at study often improve memory on later tests. A variety of such findings have been reported, and collectively they comprise the desirable difficulty principle (Bjork, 1994). E. L. Bjork and Bjork (2011) discuss four such findings. The spacing effect occurs when massing practice or study sessions within a short period produces poorer long-term retention compared to shorter study sessions distributed over a longer period (Ebbinghaus, 1913; see also Mammarella, Russo, & Avons, 2002; Toppino & Bloom, 2002). The interleaving effect refers to improved memory performance when learners study topics or practice tasks in an interleaved fashion rather than a blocked fashion (Shea & Morgan, 1979). Blocked learning often gives the appearance of better learning when short-term retention is tested, but such short-term gains are often reversed when retention is tested after a longer interval. Finally, the generation effect refers to improved retention when participants must generate a study item using a cue (e.g., the first two letters, or an anagram) rather than simply reading the study item (Jacoby, 1978; Landauer & Bjork, 1978). This effect may also relate to the testing effect, whereby testing memory for studied material produces better retention than additional study opportunities (Goldstein, 2011; Roediger & Butler, 2011). These effects fit with the general principle that difficult processing at encoding, retrieval, or both results in improved long-term retention.

Desirable Disfluency

Bjork (1994) coined the desirable difficulty principle to capture the association between difficulties in cognitive processing and improved retention. In addition to these classic effects, many recent studies also point to an association between perceptual processing difficulties and improved long-term retention. Diemand-Yauman, Oppenheimer, and Vaughan (2011) demonstrated improved memory for information presented in hard-to-read fonts compared to an unmodified font. Nairne (1988) reported what may be a related effect that involved visual masking. During an initial phase of the experiment, participants identified words presented briefly, either unmasked or pattern masked. Performance on a subsequent surprise recognition test was better for the masked than for the unmasked items (see also Hirshman & Mulligan, 1991). In another example, Rosner, Davis, and Milliken (2015) reported superior recognition memory for words presented in a blurry font than for words presented in a clear font at the time of study (but see Rosner, Davis et al., 2015, and Yue, Castel, & Bjork, 2013 for limiting conditions of this effect). Finally, Rosner, D'Angelo, MacLellan, and Milliken (2015) tested recognition memory for target words paired with interleaved distractor words. Recognition was superior for incongruent targets (i.e., a red target word interleaved with a different green distractor word) than for congruent targets (i.e., a red target word interleaved with the same word in green). Together, these results imply that perceptual difficulties can enhance encoding and retention in a manner that is broadly consistent with E. L. Bjork and Bjork's (2011) desirable difficulty principle.

Of most direct relevance to the present study, Rosner, López-Benítez, D'Angelo, Thomson, and Milliken (2017) followed up on the selective attention study described above by offsetting the target and distractor items in time. That is, rather than a target and distractor presented simultaneously, participants first viewed a single green prime word followed by a single red target word, with the task being to name only the red target word. The key issue addressed in this study was whether repetition affected recognition in the same way as congruency. Indeed, recognition memory was better for not-repeated targets than for repeated targets just as it was better for incongruent than congruent items in the prior study (Rosner, D'Angelo et al., 2015). This result is noteworthy for two reasons. First, it implies that priming is 'undesirable' in some contexts, as it may impair subsequent encoding. Second and more important, this result constitutes a counterintuitive effect in memory: Better recognition when a word is presented just once at the time of encoding than when a word is presented twice.

The Present Study

The result reported by Rosner et al. (2017) is a curious one because intuition would suggest that stimulus repetition ought to improve memory performance. Indeed, many empirical studies have documented facilitatory effects of stimulus repetition on memory performance (e.g., Lloyd, 2003; Raegh & Yassa, 2014), and it is arguably foundational in learning and education.

Clearly, the conditions that led to the result reported by Rosner et al. (2017) require further study. Toward that aim, we examined the contribution of prime encoding demands to this effect by conducting the three experiments reported in this study.

In Experiment 1, we tested two groups of participants. The method for one group constituted a close replication of the method used by Rosner et al. (2017): Two words were presented during each study trial, one after the other. Participants were to attend to and name only the second of the two words. We gave participants no instructions on what to do with the first of the two words, and therefore they were free to process it in any way they liked. The method for the second group was the same with the exception that a divided attention manipulation was implemented for the first of the two words. Specifically, two distractor digits flanked the first word on each study trial, one just left of the first letter and one just right of the last letter of the word. We asked participants to report the sum or product of the two digits as quickly and accurately as possible. In effect, the aim was to evaluate whether divided attention during encoding of the first of two words would produce the same result as an instruction not to do anything. If participants in the Rosner et al. (2017) study engaged only in relatively low-level perceptual processing, and this was key in driving the effect, then we ought to see identical results in these two groups. Specifically, better memory for not-repeated targets than for repeated targets. In Experiment 2, we examined the role of prime encoding demands further by varying the ‘depth’ of encoding (Craik & Lockhart, 1972). One group counted the vowels in each prime, a second group named each prime, and a third group attended to the meaning of each prime. The key issue addressed in Experiment 2 was whether recognition differences between repeated and not-repeated targets hinge on the encoding requirements for the primes at study. Finally, in Experiment 3, we measured memory for the not-repeated primes that preceded targets, as well as for not-repeated and repeated targets, to examine directly whether superior memory for not-repeated than repeated items hinges on particularly poor memory for primes.

Experiment 1

In the study by Rosner et al. (2017), participants saw two words during each trial in the study phase. For repeated trials the two words were identical, and for not-repeated trials the two words were different. Participants named the second word aloud but were not provided any specific instruction regarding response requirements for the first word. On the following surprise recognition memory test, recognition memory was better for not-repeated target words than for repeated target words. The aim of this experiment was to examine whether inattention to the first word during study was critical to the result reported by Rosner et al. (2017). The general idea is that not providing instructions regarding the primes on each study phase trial may have led to reduced endogenous attention to those primes. In other words, participants may have opted voluntarily not to pay attention to the primes. Perception of an unattended prime may have resulted in fluent perceptual processing of a repeated target that followed (Jacoby & Whitehouse, 1989), but without an accompanying recapitulation of semantic processing for the repeated words. If stimulus repetition in the absence of access to the meaning of primes is critical to the effect reported by Rosner et al. (2017), then a similar result ought to occur under any set of conditions that limits access to the meaning of primes.

To that end, there were two groups tested in the current experiment. One group followed a procedure that was a close replication of Rosner et al. (2017)—participants were presented two words in succession on each study trial and named only the second of the two words. The second group followed a procedure that involved divided attention for the first of two words on each study trial. For this group, participants attended to two single digit numbers that flanked this first word and reported either the sum or product of these two numbers. The key issue addressed here was whether the repetition effect reported by Rosner et al. (2017) would be observed with this divided attention procedure. If the divided attention task produces a similar result to ignoring the first word, then reduced endogenous attention to the prime may be essential to understanding this effect.

Method

Participants. Forty-eight participants (30 females; mean age = 19 years) from the McMaster University student pool completed the experiment in exchange for course credit or $10 CAD. All participants had normal or corrected-to-normal vision and spoke English fluently. A counterbalancing procedure was used to assign twenty-four participants to each group (ignore/divided attention) based on their order of arrival.

Apparatus and stimuli. The experimental program was run on a Mac Mini using the PsychoPy open source experimental software (v1.81.0, Peirce, 2007; 2009). The stimuli were displayed on a 24-in. BENQ LED monitor. The onset of naming responses for the study phase was detected using a Logitech Microphone Headset, while responses for the test phase were recorded using the keyboard. All participants were tested individually, sitting approximately 50 cm from the monitor.

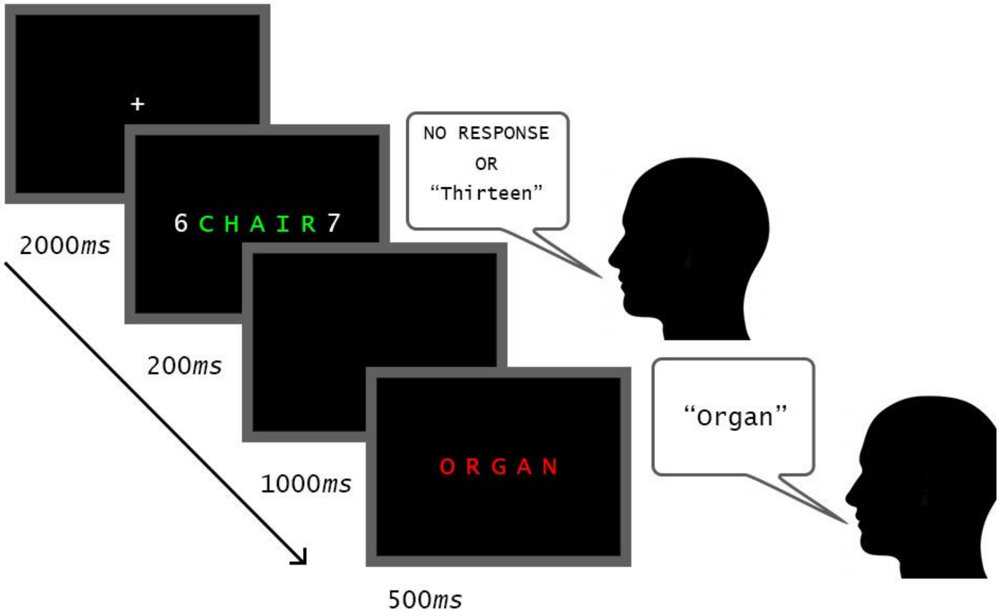

Figure 1. Depiction of stimuli in Experiment 1. The *green* word is the prime, and the *red* word is the target. In the ignore group, participants simply named the target word on each trial. In the divided attention group, participants reported either the sum or product of the two white digits and then named the red target aloud.

During the study phase, a green prime word and a red target word were presented centrally on each trial, with the prime word flanked by white digits ranging in value from 2 – 9, as shown in Figure 1. During the test phase, a red word appeared centrally, with response options “OLD” and “NEW” displayed in white in the bottom corners of the screen. In all cases, stimuli were presented with a space between each letter against a black background. Each word subtended approximately 0.8° of visual angle vertically and 5.9° horizontally. A total of 360 five-letter words were used in the experiment, all of which were high-frequency nouns (Thorndike and Lorge, 1944). The exact word lists can be found in Appendix A.

Procedure. The experiment consisted of two phases: An incidental study phase and a test phase. In the study phase, participants saw a green prime flanked by white digits, which was followed by a red target item. The between-subjects manipulation was the prime encoding task. Participants in the ignore group did nothing with the prime. Participants in the divided attention group reported aloud either the sum or product (a between subject manipulation) of the digits flanking the green prime, as quickly and accurately as possible. In both groups, participants then named the red target word aloud as quickly and accurately as possible. Each trial began with a central fixation cross displayed for 2,000 *ms*, followed by a green prime for 200 *ms*, a blank screen for 1,000 *ms*, and then a red target word for 500 *ms*. Response times (RTs) were recorded from the onset of the target word to the onset of the vocal response to the target word, as detected by a microphone headset worn by participants. Following offset of the target word, a blank screen appeared for a minimum of 1 second or until the experimenter coded the participants' response, after which the next trial began. The experimenter coded participant's responses in the study phase as correct, incorrect, or a spoil by pressing "1", "2", or "3" on the number pad of the keyboard. Incorrect responses occurred when the participant reported the wrong sum or product, named the prime word, or named the target word incorrectly. Spoils occurred when extraneous or unexpected noise was suspected to have triggered the microphone (e.g., coughing or significant ambient noise during the response window). After completion of the incidental study phase, participants completed a series of math problems for 10 minutes before proceeding to the test phase. These math problems consisted of simple arithmetic and order of operations questions. Participants were then presented with detailed instructions for the test phase both verbally and written on screen. The test phase was a surprise recognition memory task. On each trial in the test phase, a single word was presented, and participants were asked to decide whether the word was a target item from the previous study phase or a new, previously unseen lure. Participants recorded their "old" or "new" decisions via a keyboard response. Following each "old" response, participants made a remember/know classification for the word, once again via keyboard response. The remember/know instructions included detailed definitions of the difference between "remembering" and "knowing" (Rajaram, 1993). These "remember" and "know" judgments were labelled as “Type A” and “Type B”, respectively. Remember/know data were collected for exploratory purposes and are reported in Appendix B for the interest of the reader, though not discussed in depth here.[1]

Trials in the test phase began with the presentation of a central fixation cross for 2000 *ms*, followed by the presentation of a red word. The words “OLD” and “NEW” appeared in the bottom left and right corners of the screen to serve as reminders for which key corresponded to which response. The stimuli remained on screen until a response was provided via a key press: “A” for “OLD” and “L” for “NEW”. If the participant responded “OLD”, the word remained on screen and the words “OLD” and “NEW” were replaced with “TYPE A” and “TYPE B”, respectively. Stimuli remained on screen until participants responded via key press once again: “A” for “TYPE A” (a feeling of remembering) and “L” for “TYPE B” (a sense of knowing).

Design. Three hundred and sixty words were used in the experiment. The 360 words were randomly divided into six lists of 60 words (see Appendix A). For each participant, three of these were “old” word lists and three were “new” word lists. The assignment of word lists to old or new status was counterbalanced

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[1] In both conditions of Experiments 1, and in the ignore condition of Experiment 3, our remember/know data produced higher recollection for not-repeated than for repeated words (see Appendix B), but no effect for familiarity. In contrast, Rosner et al. (2017) report two experiments in which familiarity was higher for not-repeated than for repeated words, with no effect of recollection. The reason for the different effects across these two studies in unclear at this point, but we present the results in the Appendix nonetheless for the interested reader.

across participants. The three old lists served one of the following roles: prime word only (not-repeated trials), target word only (not-repeated trials), or prime and target (repeated trials). These roles were once again counterbalanced across participants. The three new lists were used to generate lure items for the test phase and were randomly assigned to the roles of prime word only (not-repeated trials), target word only (not-repeated trials), and prime and target (repeated trials). Note that because only target words were presented at test, the word list assigned to the new prime word only role was never seen by participants. Note also this is a dummy coding scheme, as new not-repeated words are undifferentiated from new repeated words to participants at test. The order of presentation of words in both phases was randomly determined. A total of 60 repeated and 60 not-repeated trials were intermixed randomly during the study phase. During the test phase, the 120 old targets were intermixed randomly with 120 previously unseen lures, for a total of 240 recognition test trials.

Results

We conducted two mixed-factor ANOVAs to examine whether the nature of the divided attention task, addition or multiplication, impacted naming times in the study phase or proportion of old responses in the test phase. Neither the main effect of divided attention task type nor any interactions involving this factor were significant in either analysis (all *p*'s > .10). Therefore, we collapsed across the two divided attention tasks in all subsequent analyses.[2]

Table 1 Mean response times (*ms*) and error rates for naming target words in the study phase

Experiment	Group	Not-Rep Targets	Repeated Target
1	Ignore	512(.007)	457(.002)
	Divided Attention	-	-
2	Vowel Count	681(.021)	595(.017)
	Name	571(.002)	534(.001)
	Semantic	665(.004)	613(.003)
3	Ignore	506(.001)	488(.001)
	Name	525(.010)	490(.006)
	Semantic	664(.024)	621(.024)

Note: Error rates are presented in parentheses.

Naming phase. Following data collection, we learned that about 60% of the correct naming times for the divided attention condition were less than 200 *ms*, suggesting that responses to the divided attention arithmetic task often overlapped with onset of the target word, which in turn stopped the timing of response to the target word prematurely. Moreover, some proportion of the correct RTs greater than 200 *ms* were also likely influenced spuriously by this problem. As such, naming times were excluded from analysis in the divided attention condition.

For the ignore condition, we eliminated from analysis RTs for incorrectly named trials and correct RTs less than 200 *ms* (2.8% of observations). The

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[2] We initially suspected the multiplication task was too difficult, motivating the switch to the addition task. As there was no indication task difficulty had any effect on the variables of interest, we collapsed across this manipulation in all subsequent analyses.

remaining RTs were submitted to an outlier elimination procedure (Van Selst & Jolicoeur, 1994) that excluded 1.5% of trials from further analysis. Mean RTs were computed from the remaining observations. These means were submitted to a paired sample *t*-test that compared the not-repeated and repeated conditions. Table 1 lists the mean RTs and error rates in each condition collapsed across participants. The analysis revealed a significant effect of repetition, *t*(1,23) = 10.80, *p* < .001, *d* = 4.50, with faster RTs for repeated (*M* = 457 *ms*, *SD* = 90 *ms*) than not-repeated trials (*M* = 512 *ms*, *SD* = 98 *ms*).

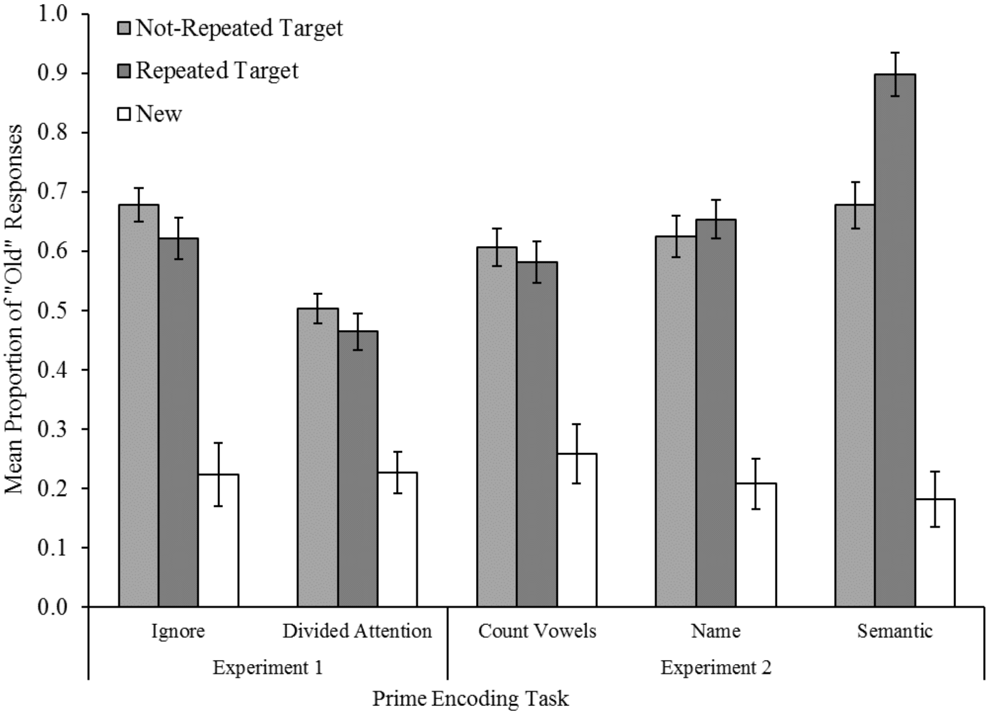

Figure 2. Mean proportion of "old" responses to old and new items as a function of repetition. Error bars reflect 95% confidence intervals (CI) corrected for between-subject variability (Morey, 2008).

Test phase. Spoil trials and items responded to incorrectly during the naming phase were excluded from the analysis of the recognition test phase for this and all following experiments.[3] The primary dependent measure in all analyses was the proportion of "old" responses. Figure 2 displays mean hit ("Old" responses to old words) and false alarm ("Old" responses to new words) rates collapsed across participants.

In the first analysis, we collapsed proportion of targets judged old across the repetition factor and then submitted the resulting values to a 2 x 2 mixed-factor ANOVA with group (ignore/divided attention) treated as a between-subjects factor and item-type (old/new) treated as a within-subject factor. The purpose of this analysis was simply to evaluate whether participants responded old more often to old items than to new items, and whether this recognition sensitivity differed for the two groups. This analysis revealed a main effect of group, $F(1,46) = 5.40$, $p = .025$, $\eta_p^2 = .105$. Participants in the ignore group ($M = .436$, $SD = .131$) responded "old" more often than did participants in the divided attention group ($M = .345$, $SD = .110$). There was also a main effect of item-type, $F(1,46) = 295.40$, $p < .001$, $\eta_p^2 = .865$, with more hits ("old" responses to old items; $M = .567$, $SD = .158$) than false alarms ("old" responses to new items; $M =$

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[3] Note that the technical problem that influenced naming times for the divided attention group did not affect the recognition analysis for the divided attention group. In other words, correct naming times that were incorrectly recorded as being lower than 200 ms did not compromise analysis of subsequent recognition of those items, as participants were blind to the naming time problem.

.225, *SD* = .141). Finally, the interaction was significant, *F*(1,46) = 17.88, $p <$ .001, η_p^2 = .280. To examine this interaction further, separate analyses were conducted for the ignore and divided attention groups. For the ignore group, the hit rate (*M* = .649, *SD* = .153) was higher than the false alarm rate (*M* = .224, *SD* = .156), *t*(23) = 12.80, $p <$ .001, *d* = 5.34. For the divided attention group, the hit rate (*M* = .484, *SD* = .115) was also higher than the false alarm rate (*M* = .227, *SD* = .128), *t*(23) = 11.81, $p <$ .001, *d* = 4.92. Together, these analyses suggest that participants in both groups produced better than chance level recognition performance, but that sensitivity was higher for the ignore group.

In a second analysis, we assessed the effect of repetition by analyzing the hit rates only. In this analysis, group (ignore/divided attention) was again treated as a between-subjects factor and repetition (not-repeated/repeated words) was treated as a within-subject factor. This analysis revealed a main effect of group, *F*(1,46) = 17.95, $p <$ .001, η_p^2 = .281, with a higher hit rate for the ignore than divided attention group. More important, there was also a main effect of repetition, with a higher hit rate for not-repeated words (*M* = .591, *SD* = .153) than for repeated words (*M* = .543, *SD* = .172), *F*(1,46) = 16.09, $p <$ .001, η_p^2 = .259. The interaction was not significant, *F*(1,46) = .61, *p* = .439, η_p^2 = .013. Our a priori interest in whether the repetition effect would be significant for each of the groups led us to conduct separate analyses for the two groups. In the ignore group, participants had higher hit rates for not-repeated words (*M* = .678, *SD* = .143) than for repeated words (*M* = .621, *SD* = .170), *t*(23) = 3.93, $p <$ .001, *d* =

1.64. Performance in the divided attention condition was similar, with more hits for not-repeated (*M* = .503, *SD* = .107) than for repeated words (*M* = .465, *SD* .138), though in this case the effect was only approached significance, *t*(23) = 2.04, *p* = .054, *d* = 0.85. The results suggest similar effects of repetition on recognition memory occur in the two groups.

Discussion

The goal of Experiment 1 was to determine whether inattention to the prime is critical to producing superior recognition for not-repeated than repeated words (Rosner et al., 2017). To address this issue, we introduced a divided attention manipulation. In the divided attention group, participants attended to the prime presentation but diverted their attention to the numbers on either side of the prime word rather than attending to the prime word itself. In contrast, in the ignore group, we gave participants no instructions for the prime word but asked them to simply name the target word that followed the prime. Importantly, the effect of repetition on recognition memory was similar across the ignore and divided attention groups, suggesting that ignoring a word produces comparable effects to divided attention.

One interpretation of these results is that processing of unattended primes can facilitate the naming of repeated relative to not-repeated targets in the study phase, without also strengthening representations that drive recognition performance at test. This might occur if participants processed unattended primes perceptually but not semantically. Perceptual processing may serve to speed naming of identical targets, but provides an inadequate basis for remembering either the prime itself or any interactive consequences of processing the prime and an identical target. Of course, to explain why memory performance is superior (rather than merely equivalent) for not-repeated than repeated trials requires an additional mechanism. To capture this property of the results, we assume that the processing discrepancy between primes and targets on not-repeated study phase trials triggers some form of exogenous (involuntary) attention shift that strengthens encoding. We discuss the nature of the processing discrepancy that produces this exogenous shift of attention in the General Discussion.

Experiment 2

We proposed that superior recognition for not-repeated items in Experiment 1 hinged at least in part on participants not having attended to the prime during the study phase. Because of inattention to primes, recognition performance for repeated targets would depend predominantly on how participants processed repeated targets on their own, rather than any joint semantic processing associated with encoding an identical prime and target. If we further assume that an exogenous shift of attention strengthens memory encoding on not-repeated trials, then one can begin to see how recognition might be better for not-repeated words.

We tested this explanatory framework in Experiment 2 by manipulating the encoding of primes, as in studies that have examined the levels of processing principle (Craik & Lockhart, 1972). Three groups participated in Experiment 2:

In the vowel count group, participants focused on orthographic processing of the primes; in the naming group, participants simply named aloud the prime; and in the semantic group, participants focused on a semantic property of the prime. As in Experiment 1, participants in all groups named the target word aloud and later completed a surprise recognition test. Inattention during prime processing may limit semantic processing, resulting primarily in processing at the perceptual level. If limited semantic processing is critical to producing better memory for not-repeated than for repeated targets, increasing 'depth' of processing should eliminate the effect. Indeed, it seems possible that semantic processing of primes would lead to a reversal of the effect.

Method

Participants. Seventy-two participants (51 females; mean age = 19 years) from the McMaster University student pool completed the experiment for course credit or a small cash remuneration of $10 CAD. All participants had normal or corrected-to-normal vision and spoke English fluently. Participants were assigned to one of three groups (name/vowel count/semantic) using a counterbalancing scheme based on their order of arrival, with 24 participants in each group.

Apparatus, stimuli, and design. The apparatus, stimuli, and design used in Experiment 2 were identical to Experiment 1 with the following exception: during the study phase, no white numbers were displayed flanking the green prime stimulus.

Procedure. The procedure used in Experiment 2 was like Experiment 1 with two exceptions during the study phase. First, the prime was displayed for 500 ms instead of 200 ms, in part to avoid the potential response overlaps observed in Experiment 1. Second, participants completed different prime encoding tasks depending on their group assignment, with methods borrowed from the depth of processing literature (Craik & Lockhart, 1972; Lockhart, Craik, & Jacoby, 1976; Craik, 2002). Participants in the vowel count group were required to report aloud the number of vowels in the prime word. In the name group, participants simply named the prime aloud. Finally, participants in the semantic group were required to answer a simple semantic question about the prime ("Can you touch this?"). RTs to the prime task were recorded in this experiment, along with naming RTs to the target word. The math distractor and test phases were identical to Experiment 1.

Results

Naming phase. RTs for correctly named targets that were greater than 200 *ms* were included in the analyses. These RTs were submitted to an outlier analysis that removed 2.4% of trials from further analysis. Mean RTs were computed from the remaining observations. The mean RTs were submitted to mixed-factor ANOVAs that treated group (vowel count/name/semantic) as a between-subjects factor and repetition (not-repeated/repeated) as a within-subject factor. Table 1 displays the means of the mean RTs and error rates collapsed across participants.

The analysis of RTs revealed a significant main effect of group, *F*(1,69) = 8.46, $p < .001$, $\eta_p^2 = .197$. Fisher's LSD tests on the RTs for the three groups revealed that naming times were faster for the name group (*M* = 552 *ms*, *SD* = 61 *ms*) than for the vowel count group (*M* = 638 *ms*, *SD* = 109 *ms*), $p < .001$, and semantic group (*M* = 639 *ms, SD* = 72 *ms*), $p < .001$, but did not differ between the latter two groups, $p = .960$. More important, there was a significant main effect of repetition, *F*(1,69) = 87.59, $p < .001$, $\eta_p^2 = .559$, with faster naming responses for repeated (*M* = 581 *ms*, *SD* = 76 *ms*) than not-repeated (*M* = 639 *ms*, *SD* = 113 *ms*) trials. The interaction between group and repetition was also significant, *F*(1,69) = 5.30, $p = .007$, $\eta_p^2 = .133$. Subsequent analyses revealed that the priming effect was significant in all three groups, $p < .001$. A follow up Fisher's LSD test on the difference scores suggests the effects was larger in the vowel count group (*M* = 86 *ms, SD* = 73 *ms*), than in either the semantic (*M* = 52 *ms*, *SD* = 48 *ms*), $p = .028$, and name (*M* = 37 *ms, SD* = 28 *ms*) groups, $p = .002$, but the latter two groups did not differ from one another, $p = .357$ (see Table 1).

Test phase. As with Experiment 1, the proportion of "old" judgments served as the primary dependent variable in the analysis of recognition performance. This measure was subjected to the same two mixed-factor ANOVAs as with the test phase in Experiment 1, albeit with three groups (vowel count/name/semantic) for the between-group factor. Figure 2 displays the mean proportions of "old" judgments in each condition, collapsed across participants.

The first analysis treated item type (old/new) as a within-subject factor and collapsed across the repetition factor, to assess overall recognition performance, and whether this performance differed between groups. There was a significant main effect of item type, *F*(1,69) = 736.38, *p* < .001, η_p^2 = .914, with more hits (*M* = .674, *SD* = .162) than false alarms (*M* = .216, *SD* = .149). The interaction was also significant, *F*(2,69) = 21.82, *p* < .001, η_p^2 = .387. To examine this interaction further, we compared hits and false alarms separately for each group using two-tailed paired sample t-tests. Hits exceeded false alarms in all three groups, *p* < .001. A follow up Fisher's LSD of the corrected hit rates (hits minus false alarms) determined sensitivity was highest in the semantic group (*M* = .606, *SD* = .143), which was superior to both the name group (*M* = 432, *SD* = .154) and ignore group (*M* = .337, *SD* = .132), both *p*'s < .001. Between the latter two groups, there was also a significant difference in favour of the name group, *p* = .024 (see Figure 2).

The second analysis observed only the hit rates, with group treated as a between-subject factor and repetition (repeated/not-repeated) treated as a within-subject. This analysis produced both a main effect of group *F*(2,69) = 12.47, *p* < .001, η_p^2 = .266, and a main effect of repetition, *F*(1,69) = 35.95, *p* < .001, η_p^2 = .343. For the group effect, Fisher's LSD tests showed superior hit rates for the semantic group than both the name and vowel count groups (*p* < .001 for both comparisons), though the latter two did not differ from one another (*p* = .276). For the repetition effect, participants recognised repeated words (*M* = .711, *SD* =

.200) better than not-repeated words (*M* = .637, *SD* =.152). This effect was qualified by an interaction between group and repetition, *F*(2,69) = 35.83, *p* < .001, η_p^2 = .510. The significant interaction led us to analyse the effect of repetition separately for each group, again using two-tailed paired sample t-tests. For the semantic group, the hit rate was higher for repeated targets (*M* = .898, *SD* = .102) than for not-repeated targets (*M* = .678, *SD* = .679), *t*(23) = 8.94, *p* < .001, *d* = 3.73. In contrast, for the name and vowel count groups the effect of repetition was not significant, *p* > .10. These results are in line with our prediction that the effect of repetition depends on prime encoding demands.

Discussion

In contrast to Experiment 1, in Experiment 2 we instructed pariticpants to attend to the primes, with the specific encoding requirements for the prime varying across three groups. The purpose of the experiment was to examine whether the repetition effect on recognition memory would vary as a function of processing of the primes. Indeed, there were null effects of repetition on recognition performance in the vowel count and name groups, and greater sensitivity for repeated than for not-repeated targets in the semantic group. These results demonstrate the counter-intuitive finding reported by Rosner et al. (2017) does not always occur with the repetition method used here. Specifically, when primes are encoded in such a way that participants are likely to remember them at test (according to the levels of processing principle), recognition performance is better for repeated than for not-repeated targets.

Experiment 3

The results from Experiments 1 and 2 are consistent with the proposal that relatively poor recognition performance for repeated targets hinges on poor memorability of primes that accompanies inattention to the semantic properties of those primes. However, the evidence favouring this proposal to this point has been indirect. In the present experiment, the aim was to directly evaluate this idea by measuring how well participants could remember the primes from the study phase. To do this, we tested recognition of not-repeated primes in addition to targets (note that recognition of repeated primes could not be tested separately from recognition for repeated targets). Three prime encoding groups were included in this experiment: an ignore group like that in Experiment 1, a name group like that in Experiment 2, and a semantic group like that in Experiment 2. Two hypotheses related to prime recognition were of interest.

The first hypothesis was straightforward: The repetition effect in recognition observed for targets ought to closely mirror recognition of primes, with the worst prime recognition in the ignore group and the best prime recognition in the semantic group. The second hypothesis relates to the relative recognition sensitivity for not-repeated primes and repeated targets. The rationale for examining this contrast is that recognition of primes could conceivably drive recognition for repeated targets despite the nominal task being to recognise the named targets from the study phase. For instance, participants could respond “old” to the repeated item TRUCK not because they remembered encoding the word TRUCK as a named target, but because they remembered encoding the word TRUCK as a prime. In this sense, it is useful to consider recognition performance for repeated targets in the context of how well participants recognise primes on their own.

Method

Participants. Seventy-two participants (60 females; mean age = 19 years) from the McMaster University student pool completed the experiment for course credit or a small cash remuneration of $10 CAD. All participants had normal or corrected-to-normal vision and spoke English fluently. Participants were assigned to one of three groups (ignore/name/semantic) using a counterbalancing scheme based on their order of arrival, with 24 participants in each group.

Apparatus, stimuli, and design. The apparatus, stimuli, and design used in Experiment 3 were identical to Experiment 2 with the following exceptions during the test phase. First, words were presented in white. Second, the proportion of new and old words at test was altered such that there were now 60 new words and 180 old words. The 180 old words consisted of 60 not-repeated primes, 60 not-repeated targets, and 60 repeated targets. To accommodate this change in experimental design, the size and number of word lists were altered, but the global word pool remained the same. As in prior experiments, the counterbalancing constraints ensured that each word in the global word pool occurred equally often as a not-repeated prime, a not-repeated target, and a repeated target.

Procedure. The procedure used in Experiment 3 was similar to Experiment 2 with the following exceptions. There were three groups tested in this experiment: an ignore group like that tested in Experiment 1, a name group like that tested in Experiment 2, and a semantic group like that tested in Experiment 2. Participants in the ignore group simply named the red word aloud on each study phase trial. Participants in the name group named both the prime and target word aloud. Finally, in the semantic group, participants answered a simple semantic question about the prime ("Can you touch this?"). During the study phase, we collected only naming RTs for target words. Finally, and most importantly, the test phase was altered to include the not-repeated primes in addition to not-repeated and repeated targets.

Results

Naming phase. RTs for correctly named targets that were greater than 200 *ms* were included in the analyses. These RTs were submitted to an outlier analysis that removed 1.7% of trials from further analysis (Van Selst & Jolicoeur, 1994). Mean RTs were computed from the remaining observations, and these mean RTs were submitted to a mixed factor ANOVA that treated group (ignore/name/semantic) as a between-subjects factor and repetition (not-repeated/repeated) as a within-subject factor. The means of participants' mean RTs and error rates in each condition are displayed in Table 1.

The analysis of RTs revealed a significant main effect of group, $F(2,69) = 16.21$, $p < .001$, $\eta_p^2 = .320$. Fisher's LSD tests on the RTs for the three groups revealed that naming times were slower for the semantic group (*M* = 644 *ms*, *SD* = 105 *ms*) than for the ignore (*M* = 497 *ms*, *SD* = 113 *ms*) and name groups (*M* = 508 *ms*, *SD* = 73 *ms*, *p* < .001 for both comparisons), but did not differ between the latter two groups, *p* = .691. More important, there was a significant main effect of repetition, *F*(1,69) = 45.04, *p* < .001, η_p^2 = .395, with faster naming responses for repeated (*M* = 533 *ms*, *SD* = 114 *ms*) than for not-repeated (*M* = 564 *ms*, *SD* = 125 *ms*) trials. The interaction between group and repetition was not significant, *F*(2,69) = 2.31, *p* = .107, η_p^2 = .063.

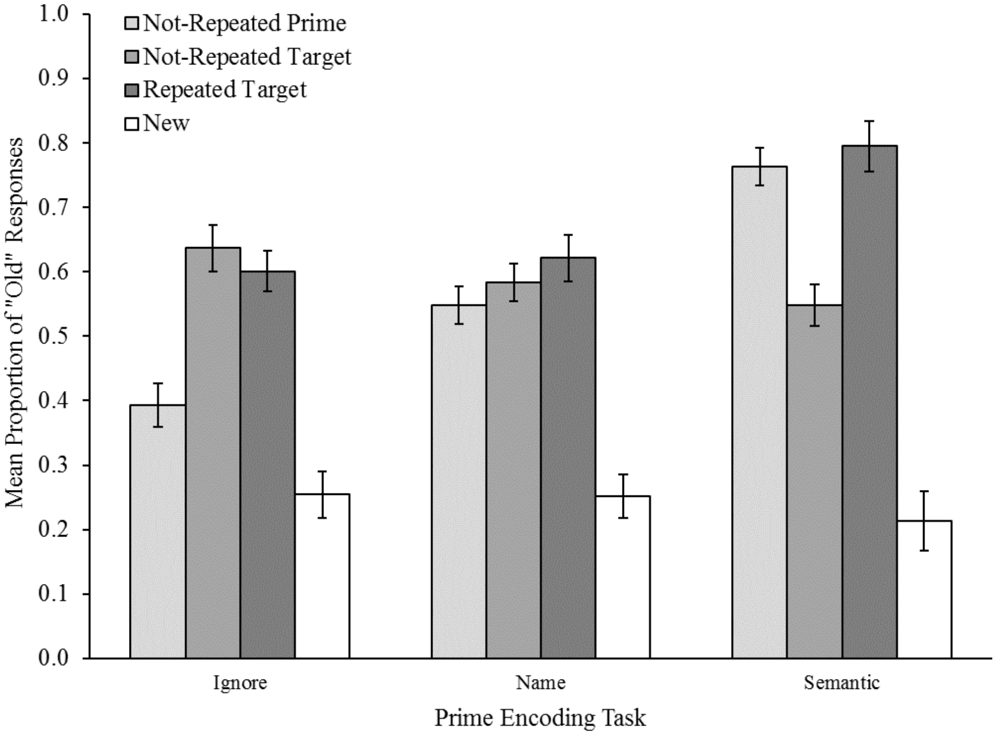

Figure 3. Mean proportion of "old" responses to old and new item**s** as a function of item type. Error bars reflect the 95% confidence intervals (CI) corrected for between-subject variability (Morey, 2008).

Test phase. The mean proportions of “old” judgments in each condition, collapsed across participants, are displayed in Figure 3. The analysis strategy for the recognition test phase had four components. The first two components involved analyses of recognition memory that corresponded to those conducted in Experiments 1 and 2. In effect, we were interested in whether the results from this experiment offered a close replication of the recognition results in our prior experiments. The third component of our analysis examined recognition performance for the not-repeated primes across the three groups. As noted above, the straightforward prediction is that repetition effects revealed in the first analysis ought to mirror closely the overall recognition performance for not-repeated primes in this second analysis. Finally, the fourth component of our analysis strategy involved a comparison of recognition performance for not-repeated primes and repeated targets across the three groups. This comparison allowed us to evaluate whether recognition for primes always improved with a repeated naming event.

Analysis of overall recognition performance. The first analysis used proportion of “old” judgments as the dependent variable, with group (ignore/name/semantic) as the between-subjects factor, and item type (old/new) as the within-subject factor. The goal was to assess recognition sensitivity overall, and whether sensitivity differed across these groups.

The analysis revealed a significant main effect of item type, $F(1,69) = 882.95$, $p < .001$, $\eta_p^2 = .928$. Participants produced more hits ($M = .610$, $SD =$

.159) than false alarms (*M* = .240, *SD* = .147). The interaction between group and item type was also significant, *F*(2,69) = 23.65, *p* < .001, η_p^2 = .407, suggesting recognition performance varied across groups. As with Experiment 2, we compared group corrected hit rates using Fisher's LSD to examine the interaction. Sensitivity was greater in the semantic group (*M* = .489, *SD* = .125) than either the ignore group (*M* = .290, *SD* = 097) or the name group (*M* = .332, *SD* = .092), both *p*'s < .001. Performance did not differ between the ignore and name group, *p* = .167 (see Figure 3). These results are predictable from and consistent with expectations generated from Experiments 1 and 2.

Analysis of repetition effects. The second analysis used hits as the dependent variable, with group (ignore/name/semantic) serving as a between-subjects factor, and repetition (not-repeated/repeated target) as a within-subject factor. The purpose was to analyse the impact of prime encoding demands on recognition memory sensitivity for repeated and not-repeated targets across the three groups.

The main effect of repetition was significant, *F*(1,69) = 44.22, *p* < .001, η_p^2 = .391, with a higher hit rate for repeated words (*M* = .673, *SD* = .179) than for not-repeated words (*M* = .590, *SD* = .169). However, this main effect was qualified by a significant interaction between group and repetition, *F*(2,69) = 46.31, *p* < .001, η_p^2 = .571. To examine the interaction further, we compared the two repetition conditions separately for each group. In the ignore group, the repetition effect was similar to that in Experiment 1, with a higher hit rate for not-repeated (*M* = .637, *SD* = .164) than for repeated words (*M* = .601, *SD* = .148), though in this case the effect only approached significance, $t(23) = 1.91$, $p = .069$, $d = 0.40$. In the name group, the repetition effect resembled that observed in Experiment 2, with a higher hit rate for repeated (*M* = .584, *SD* = .177) than for not-repeated words (*M* = .548, *SD* =.162) that approached significance, $t(23) = 1.78$, $p = .089$, $d = 0.37$. For the semantic condition, however, the hit rate was higher for repeated words (*M* = .795, *SD* = .148) than for not-repeated words (*M* = .548, *SD* = .174), $t(23) = 10.28$, $p < .001$, $d = 2.14$. Broadly speaking, the repetition effects observed here were similar to those observed in our prior experiments.[4]

Recognition of primes. To compare the recognition of not-repeated primes across groups, one-way ANOVAs were conducted on hit rates that treated group (ignore/name/semantic) as the lone between-subject factor. The purpose was to assess whether recognition of not-repeated primes produced a 'depth of processing' effect, and whether these effects can explain observed repetition effects.

The analysis resulted in a main effect of group, $F(2,69) = 35.89$, $p < .001$, $\eta_p^2 = .571$. Post-hoc Fisher's LSD tests revealed recognition memory in the semantic group (*M* = .763, *SD* = .136) was superior to both the ignore (*M* = .393,

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[4] The borderline significance of repetition effects in both the ignore and name groups led us to compare their difference scores using Fisher's LSD. Performance significantly differed, $p = .017$, providing additional evidence that the directionality of the effect in each group differs.

SD = .155, *p* < .001) and name group (*M* = .548, *SD* = .163, both *p* < .001). The memory for primes also differed between the latter two groups, with the name group performing better than the ignore group (*p* = .001). This pattern of prime recognition corresponds closely to the repetition effects reported in our prior analysis, where there was a substantial repetition benefit for the semantic group, a modest repetition benefit for the name group, and a repetition cost for the ignore group.

Recognition of repeated targets relative to not-repeated primes. To compare recognition performance for repeated targets to that of not-repeated primes, we subjected hit rates to a 3 x 2 mixed-factor ANOVAs that treated group (ignore/name/semantic) as a between-subjects factor, and item type (not-repeated prime/repeated target) as a within-subject factor. The purpose of this analysis was to assess whether the diverse types of prime encoding led to repetition effects above and beyond what can be explained by differences in prime encoding itself.

The analysis of hit rates revealed a main effect of group, *F*(2,69) = 23.60, *p* < .001, η_p^2 = .406. Fisher's LSD revealed that hit rates were higher for the semantic group (*M* = .779, *SD* = .134) than both the name (*M* = .585, *SD* = .161) and ignore groups (*M* = .497, *SD* = .140), *p* < .001 in both cases. The latter two groups also differed from one another, *p* = .041. Returning to the main analysis, there was also a main effect of item type, *F*(1,69) = 67.86, *p* < .001, η_p^2 = .496, that was qualified by a significant interaction between group and item type, *F*(1,69) = 17.36, *p* < .001, η_p^2 = .335. To analyse this interaction further, we compared the two item types separately for each prime encoding group. For the ignore group, hit rates were significantly higher for repeated targets than for not-repeated primes, $t(23) = 8.79$, $p < .001$, $d = 1.83$. This result again demonstrates that memory for primes was particularly poor for the ignore group. For the name group, hit rates were also higher for repeated targets than for not-repeated primes, $t(23) = 3.17$, $p = .004$, $d = 0.66$. This result suggests that naming a word twice on a single study phase trial improved recognition beyond the level achieved for a word named just once as a prime. Finally, for the semantic group, there was a trend favouring higher hit rates for repeated words than for not-repeated primes that approached significance, $t(23) = 1.73$, $p = .098$, $d = 0.36$. Considered together, these results suggest that encoding a prime and then producing a naming response to an identical target typically improves recognition performance above and beyond recognition of the prime itself.[5]

Discussion

The purpose of the present experiment was to examine recognition memory for primes in the context of the repetition effects measured in prior experiments. Indeed, the repetition effects observed here were like those observed in prior experiments. First, as reported by Rosner et al. (2017), and as observed in Experiment 1, recognition was better for not-repeated than repeated

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[5] Indeed, this result fits well with studies of the production effect (MacLeod, Gopie, Hourihan, Neary, & Ozubko, 2010; Putnam, Ozubko, MacLeod, & Roediger, 2014). We thank Mike Humphreys for identifying the connection between our current work and the production effect.

targets when participants ignored the primes in the study phase. Although this result only approached significance in the present experiment, the reliability of this effect across six similar variants of this procedure (Rosner et al., 2017; Experiment 1 of the present study) offers plenty of supporting evidence that there is a real and replicable difference in recognition memory between not-repeated and repeated target conditions. Second, recognition was just slightly better for repeated than not-repeated targets when participants read the primes in the study phase. Again, this effect only approached significance here, but several similar variants of this procedure have consistently pointed to a small benefit for repeated items when participants read primes aloud (Rosner et al., 2017, Experiment 4; Experiment 2 of the present study). Third, recognition was substantially better for repeated than not-repeated targets when participants processed the primes semantically. This result corresponds closely to that observed in Experiment 2. Altogether, the repetition effects observed here constitute close replications of those seen in prior experiments.

Given the similar pattern of repetition effects observed here and in prior studies, the analysis of prime recognition was noteworthy on two counts. First, the pattern of prime recognition across the three groups closely mirrored the pattern of repetition effects across groups. Memory for primes was especially poor in the ignore group, predictably better in the name and semantic groups, with the best memory for primes occurring when participants encoded semantically. Second, comparison of recognition for not-repeated primes and repeated targets suggests that repetition did benefit recognition for the name and semantic groups beyond prime memory alone. This result suggests that at least some component of the advantage for repeated over not-repeated targets in these conditions relates to encoding the same word twice, rather than being a spurious consequence of particularly good recognition of the primes alone.

General Discussion

The purpose of the present study was to examine how prime encoding demands influence memorability of targets using an immediate priming method. We were particularly interested in the influence of prime encoding demands on the counter-intuitive result reported by Rosner et al. (2017): better recognition for not-repeated targets than for repeated targets. Experiment 1 produced two notable results. First, the ignore group replicated the pattern of results reported by Rosner et al. (2017), with better recognition for not-repeated than repeated targets. Second, the divided attention group produced a similar result. Attention to digits that flanked the prime word rather than to the prime word itself also produced better recognition for not-repeated words than repeated words. These results confirm that not-repeated targets in an immediate priming method produce a similar desirable difficulty effect to that observed with incongruent word pairs in a selective attention method (Rosner, D’Angelo et al., 2015). Further, the results suggest inattention to primes is critical to the counter-intuitive repetition effect reported here and in Rosner et al. (2017).

In Experiment 2, we examined how ‘depth’ of prime encoding (Craik & Lockhart, 1972) affected recognition memory for repeated targets. Prime encoding tasks that directed attention to orthographic qualities of the prime produced recognition that was no better for repeated than not-repeated targets. In contrast, an encoding task that directed attention to phonological and semantic qualities of the prime produced superior memory for repeated than not-repeated targets. Considered together, the results of Experiments 1 and 2 demonstrate clearly that immediate repetition effects in recognition memory depend on how participants process primes.

In Experiment 3, we assessed the influence of prime encoding on recognition of repeated items by testing recognition of not-repeated primes. If recognition of repeated targets hinges closely on memory for primes, then recognition of not-repeated primes ought to parallel the repetition effects, with particularly poor recognition of ignored not-repeated primes and particularly good recognition of semantically processed not-repeated primes. Indeed, this is precisely what we observed. Further, if recognition of repeated items is driven by processing of both targets and primes, rather than primes on their own, then recognition of repeated targets ought to be superior to the recognition of not-repeated primes. Repeated targets were generally recognised more successfully than not-repeated primes. Participants recognised words presented as both prime and target better than words presented only as a prime, though in the case of the semantic condition the effect only approached significance.

The results confirm that when participants encode primes in a manner that supports later remembering (e.g., semantically processing the prime), encoding a word twice in rapid succession produces superior recognition to encoding a word just once. However, when participants encode primes in a manner that does not support later remembering (e.g., when ignoring the prime), encoding a word just once as a target can produce superior recognition than encoding a word twice in rapid succession (Rosner et al., 2017). As noted earlier, superior recognition for not-repeated than repeated items may imply that an exogenous shift of attention to not-repeated targets up-regulates encoding in a manner that facilitates later recognition. The following section discusses this possibility in more detail.

Exogenous Attention, Memory Encoding, and Recognition Memory

The superior recognition for not-repeated than repeated targets observed in Experiments 1 (ignore and divided attention groups) and 3 (ignore group) is a curious result that requires an explanation. A straightforward account of this effect attributes it simply to differences in 'time-on-task'. According to this view, faster naming times for repeated targets imply that participants processed these targets to a lesser degree, which in turn accounts for their relatively poor recognition. Put differently, naming times could offer a measure of extensiveness of encoding, which in turn directly impacts the likelihood of recognition. To address this possibility for each of our experiments, we compared response times for remembered and forgotten items using a two-tailed paired sample *t*-test. None of these comparisons proved significant ($p > .10$), suggesting that naming time on its own does not offer a measure of the extensiveness of encoding that predicts memory performance (see Rosner et al., 2017 for other related analyses).

An alternative view assumes that processing difficulty encountered on not-repeated trials cues attention exogenously in a manner that up-regulates encoding, which in turn results in improved recognition. Here we discuss two possible processing difficulties that might drive these shifts in exogenous attention: (1) difficulties in lower-order perceptual processing, and (2) differences in higher order event encoding.

Perceptual processing difficulty. Experiencing difficulty in ongoing perceptual processing may pull exogenous attention automatically to the encoding of a target item. One might think of this process as a form of cognitive control operation that up-regulates the resources dedicated to encoding in accord with the need for such resources. This up-regulation of resources allocated to encoding could, in turn, affect the quality and depth of encoding. This idea resembles the 'hedonic marking' principle (Winkielman et al., 2003). By this view, ongoing evaluation of processing fluency is an adaptive means by which organisms assess the valence of experiences and the need for additional encoding, with the allocation of attentional resources up-regulated to encode unfamiliar information, and perhaps down-regulated to conserve energy for information that is already well represented. Thus, in the context of the present experiments, participants encode repeated words 'undesirably', in the sense that their familiarity down-regulates their encoding.

Although none of our current results uniquely favour this explanation, future research that directly manipulates the perceptual processing difficulty associated with repeated target words may be prudent. Mammarella et al. (2002) found that changing the font between repeated presentation of non-words was sufficient to reduce short-term perceptual priming of those stimuli. If changing the font for repeated target words eliminates or reverses our observed deficit in recognition memory for repeated words, this result would provide compelling evidence for the perceptual processing difficulty account proposed here. Evidence suggests that attentional adaptations that accompany increased processing difficulty do not always result in improved memory performance (Richter & Yeung, 2012; Chiu & Egner, 2015), but at least one does. We must sort out which types of difficulties do and do not provide recognition memory benefits in subsequent work.

New event encoding. Kahneman, Treisman and Gibbs (1992; see also Hommel, 1998; 2004) proposed that onset of a stimulus rapidly and automatically cues a process aimed at determining whether the current stimulus corresponds to an existing event representation. If so, an updating process occurs integrating the current stimulus with the previous event representation. If not, a new event representation is created. Zacks and colleagues describe a related set of ideas focusing on the importance of event segmentation processes (Zacks & Swallow, 2007; Zacks & Tversky, 2001). The basic idea underlying both theoretical frameworks is that identification of the boundaries between events is critical to perception and memory. In the present experiments, the transition between prime and target on not-repeated trials might well serve as an event boundary, whereas no such event boundary exists for the transition between prime and target on repeated trials. If processing that occurs at event boundaries provides a basis for remembering items on a recognition test, then this would explain why recognition is superior for not-repeated than repeated targets.

Henson and Gagnepain (2010) forward a related proposal. They suggest that memory encoding and retrieval are driven primarily by 'prediction errors'. By this view, when the forward transmission of bottom-up sensory information conflicts with semantic and episodically generated expectations, there is an up-regulation of encoding and improvement to subsequent retrieval (Henson & Gagnepain, 2010). This proposal is like that described above on event encoding in that a mismatching signal triggers the up-regulation of encoding, in this case between contextually specific expectations and experience.

Relation to the Spacing Effect in Remembering

In the experiments reported here, stimulus repetition was immediate; that is, the interval between prime and target was just one second. As such, one might reasonably ask whether the results observed here (see also Rosner et al., 2017) relate to the distributed practice principle (Baddeley & Longman, 1978; Ebbinghaus, 1913) or more specifically to the spacing effect (Bjork & Allen, 1970). Contemporary theories of the spacing effect fall roughly into two classes:

deficient processing theories and contextual variability theories (Russo, Parkin, Taylor, & Wilks, 1998).

Deficient processing theories propose that the spacing effect is due to diminished processing of the second occurrence of a target item when it occurs shortly after a first occurrence. For recognition memory, which Hunt and Einstein (1981) argue depends heavily on item-specific memory, Challis (1993) suggests that the spacing effect may be driven by deficient processing of immediate compared to spaced repetitions brought on by short-term perceptual priming. In contrast, contextual variability theories propose spaced repetitions provide more distinct contextual cues than immediate repetitions, affording an advantage for later remembering. Both classes of theory predict that memory for repetitions improves with the forgetting that accompanies longer intervals between repetitions (Greene, 1989). However, only the deficient processing theories have a mechanism that directly targets poor encoding of repetitions. In this sense, deficient processing theories of the spacing effect seem best equipped to explain superior recognition for not-repeated than repeated items observed in this study (see also Rosner et al., 2017). We propose here that more robust exogenous orienting of attention for novel than familiar events may underlie this deficient processing of repeated items. Critically, this interpretation provides a potential mechanism to explain desirable difficulty effects observed for not-repeated targets.[6]

Conclusion

To the best of our knowledge, the findings reported by Rosner et al. (2017) and replicated here in Experiments 1 and 3 constitute a novel effect- a deficit in recognition memory for words processed twice compared to words processed once. Specifically, recognition memory can be superior for a target preceded by a different prime than for a target preceded by an identical prime. The present study provides evidence that this effect depends on inattention to the primes. When participants attended to and encoded primes semantically, recognition was substantially better for repeated than for not-repeated targets. A key issue for future research to address is the relation between the mechanism that produces inferior memory for repeated items in the present experiments and the mechanism that underlies well-studied spaced repetition and distributed learning effects.

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[6] Of course, it is equally valid to consider the results an ‘undesirable advantage’ for processing of repeated targets. The current design does not allow us to discriminate between benefits of novelty and costs of familiarity.

Appendix A

Word lists: Experiments 1 and 2

Word list 1:

CURVE, MONEY, TOWER, WHEEL, TABLE, CHAIR, DROVE, GROUP, STEEP, STERN, DAILY, TOTAL, WATCH, PILOT, WATER, SHORT, NOVEL, MONTH, SHEER, CABLE, GUIDE, CATCH, BRIDE, CLEAN, TITLE, SPRAY, SOLID, MAJOR, CLIMB, THROW, COAST, OLIVE, RIVAL, TRUTH, IDEAL, GLOVE, STAMP, JEWEL, ADULT, PURSE, GUARD, SWIFT, WORST, CHARM, UNCLE, SIGHT, FLASH, STORY, JUICE, TRADE, PITCH, SAUCE, FANCY, SHOCK, STRIP, BLIND, BROOK, START, GLARE, DRIVE

Word list 2:

TOUGH, CLERK, PEACH, PHONE, KNOCK, OFFER, GLEAM, WOUND, SPEED, PUPIL, LIGHT, VALUE, EVENT, CREEK, RANCH, CRASH, TRACE, MOTOR, SHAPE, SMART, EXTRA, SHIRT, VOICE, ANGLE, STAKE, RADIO, MATCH, TODAY, BRICK, SLOPE, BREAD, SWEAR, PARTY, BREAK, CHILL, TRAIN, UPPER, WORLD, GLASS, MOVIE, PROOF, NOBLE, STRAW, SCORE, BASIS, CLASS, EMPTY, STATE, AGENT, MAGIC, FRONT, FROWN, CABIN, BIRTH, FLOOR, CIGAR, PIANO, CHOKE, SLIDE, COUNT

Word list 3:

TWIST, FEVER, TRICK, DELAY, TOAST, SPOON, DREAM, CHEST, STUFF, CRAWL, LUNCH, INNER, TASTE, BENCH, NURSE, CHAIN, NERVE, RANGE, ISSUE, CLOUD, CHASE, HONEY, HORSE, PLANE, OWNER, LIMIT, PRESS, ROUND, PAINT, PRIZE, ASIDE, CANDY, TREAT, BLANK, SHAME, STOOP, MOUTH, FLAME, ANKLE, BATHE, LAUGH, MUSIC, SCALE, POUND, OCEAN, MIGHT, CLAIM, FAINT, YIELD, CHIEF, HEART, ONION, CHEER, BRAND, PLANK, SLEEP, STUDY, TENSE, GUESS, LEAST

Word list 4:

STOLE, SHAKE, CHILD, ROUGH, CLIFF, ORDER, REBEL, DRESS, ELBOW, WAGON, SHARP, QUOTE, TIMER, TRAIL, CROWN, STAGE, JELLY, LINEN, DRAIN, STALK, HURRY, PORCH, RIGHT, STEEL, BRUSH, TRUNK, BUNCH, PENNY, BLOCK, SERVE, STONE, SHARE, BRAIN, EARTH, SCENE, FLOUR, CHEEK, GRASS, PLANT, JUDGE, CRUMB, PRINT, SPOIL, SPOKE, SHELL, OTHER, COURT, SHEET, PAUSE, SUGAR, STICK, BLOOM, TEETH, PRIDE, WHILE, SKIRT, BLAZE, GLORY, TRACK, SPELL

Word list 5:

CORAL, FRAME, SHORE, GRAIN, STORE, BOAST, DOUBT, SATIN, REACH, SLICE, PEARL, GRASP, PRICE, ORGAN, TRUCK, STOCK, PASTE, CRACK, COVER, SWING, WHIRL, CLOCK, RIVER, SPACE, STEAL,

LEVEL, DEPTH, STILL, ROUTE, SPLIT, SCARE, FENCE, KNIFE, ACTOR, POINT, THING, FLOAT, SALAD, GRIEF, SHINE, SMELL, QUIET, SHIFT, SCENT, LEMON, ELECT, FRUIT, GUEST, MIDST, FLUSH, PIECE, OPERA, GRADE, SWEET, QUICK, NOISE, SMALL, CROSS, STAND, TROOP

Word list 6:

VISIT, APPLE, STYLE, FIELD, BOUND, SWEAT, METAL, LEAVE, DRINK, WRIST, THUMB, MORAL, DANCE, STARE, GRANT, POISE, STOVE, GROAN, SOUND, HOUSE, SHOUT, DRIFT, SENSE, CLOTH, CROWD, LAYER, STORM, WASTE, SMILE, ROAST, SHRUG, PLATE, TRUST, PLAIN, CRUSH, COACH, HOTEL, PAPER, YOUTH, CHECK, SAINT, WRECK, SPORT, EQUAL, SMOKE, STAFF, BURST, BOARD, LOCAL, STEAM, FORCE, ALARM, SHADE, NIGHT, WOMAN, MODEL, UNDER, WHEAT, BRIEF, TOUCH

Appendix B

		Recollection			Familiarity		
		Not-repeated		Repeated	Not-repeated		Repeated
Exp.	Group	Prime	Target	Target	Prime	Target	Target
1	Ignore		.367	.316*		.268	.232
	Div. Attention		.150	.115*		.187	.172
2	Vowel Count		.238	.223		.236	.221
	Name		.273	.310		.276	.278
	Semantic		.251	.595***		.391	.544**
3	Ignore	.077	.272	.234*	.091	.254	.231
	Name	.178	.194	.248**	.201	.234	.245
	Semantic	.481	.204	.520***	.314	.224	.363***

Estimates of recollection and familiarity derived from the Independence/remember-know procedure (Yonelinas, 2002; Yonelinas & Jacoby, 1995). Asterisks represent contrasts of within-subject repetition effects. (* $p < .05$; ** $p < .01$; *** $p < .001$)

CHAPTER 3 – Immediate Repetition and Deficient Processing: Contributions to the Spacing Effect in Recognition Memory

Collins, R. N., Milliken, B. (under review; submitted 10 July 2018).
Acta Psychologica, Manuscript ID: ACTPSY_2018_299

Preface

The experiments in the previous chapter demonstrate the importance of the prime encoding task to the repetition decrement effect. This result is broadly consistent with deficient processing theories of the spacing effect. Chapter 3 was intended to investigate a potential unitary account of both the repetition decrement and spacing effect. To that end, we manipulated the spacing between the repetition of prime-target pairs to investigate the effect on subsequent memory. The results from four experiments confirmed that the repetition decrement effect depends on the spacing of prime-target pairs. Spacing the repetition of prime-target pairs reversed the repetition decrement effect. This interaction indicates that transient, deficient processing triggered by the retrieval of earlier representations drives both the spacing and repetition decrement effect.

Abstract

Rosner, Lopez-Benitez, D’Angelo, Thomson, and Milliken (2018; see also Collins, Rosner & Milliken, 2018) reported a novel recognition memory effect. In an incidental study phase, participants named target words preceded either by an identical prime or by a different prime. In the following test phase, recognition memory was better for targets preceded by different primes than for targets preceded by identical primes during the study phase. The present study explores whether this effect is mediated by the spacing between repeated items, as in the well-known spacing effect (Ebbinghaus, 1885). Indeed, when the encoding of primes was controlled carefully, immediate repetition resulted in a cost in recognition performance, whereas spaced repetition (by about 10 minutes) resulted in a benefit in recognition performance. The results are discussed in relation to the link between impaired encoding of repeated events and the spacing effect.

Introduction

Most of us are familiar with the phrase ‘practice makes perfect’. This motivational idiom aligns with intuition and is confirmed by many real-world observations. Much empirical research also supports this view – repeated opportunities to encode a stimulus improves subsequent memory retrieval (Bjork & Allen, 1970; Greene, 1989) and perceptual identification (Jacoby & Dallas, 1981). These observations suggest that stimulus repetition strengthens underlying memory representations.

The present study focuses on a contradictory idea, that stimulus repetition can weaken memory encoding. This alternative proposal was the focus of two recent studies (Collins, Rosner & Milliken, 2018; Rosner, Lopez-Benitez, D’Angelo, Thomson, & Milliken, 2018). In both studies, participants read aloud a red target word preceded by a briefly presented green prime word. On half of the trials the prime and target were the same (repeated trials), and on the other half of the trials the prime and target were different (not-repeated trials). When primes were poorly encoded, recognition sensitivity in the following test phase was better for not-repeated targets than for repeated targets from the study phase. We call this the repetition decrement (RD) effect.

Of particular interest here is the relation between the RD effect and the spacing effect (Bjork & Allen, 1970; Ebbinghaus, 1885). The spacing effect is the ubiquitous finding that memory for items encoded more than once benefits from spacing between repetitions. Although processes responsible for the RD effect could reasonably contribute to the spacing effect, to our knowledge there are no demonstrations within the spacing effect literature in which repeated study impairs memory performance compared to an item that is encoded only once. Our primary aim here is to examine whether the RD effect reported in our prior studies constitutes such an effect – that is, an effect implicating deficient encoding of repeated items driven by the same processes that produce the spacing effect. The deficient processing theory of the spacing effect presents a compelling opportunity for a unified theory of both effects.

The Deficient Processing Theory of Spacing Effects

Prior studies suggest that common mechanisms produce the spacing effect across a variety of cued-memory tests (Greene, 1989; Russo, Mammarella, & Avons, 2002). Greene (1989) defines cued-memory tests as those in which the experimenter supplies retrieval cues. These cues can be associated stimuli, as in tests of cued recall, or copy cues, as in tests of recognition and frequency discrimination. Cued-memory tests are thought to rely predominantly on item-specific encoding (Hunt & Einstein, 1981), so the implication is that repeated items presented close together in time are associated with some form of "deficiency" in item-specific processing. There is, however, debate over whether this deficient processing for short spacing is the result of voluntary (Greene,

1989) or automatic processes (Hintzman, 1976; Russo et al., 2002; Toppino, Kasserman, & Mracek, 1991)[1].

Greene (1989) conducted a study that tested recognition performance while varying both the intentionality of learning and the spacing of repetitions. Participants were presented a list of common nouns and adjectives at a rate of one every 10 seconds, and the words could appear 1, 2, 3, or 4 times with lags between repetitions of 0, 1, 2, 4, 8, or 16 items. When participants were told before the study phase that their memory would be tested, there was a significant spacing effect. When participants were not told their memory would be tested, however, no spacing effect was found. The importance of intentionality to the spacing effect has been noted in other studies as well (Russo, Parkin, Taylor, & Wilks, 1998; Shaughnessy, 1977). According to Greene (1989), when participants encounter a familiar item they may infer that it is already well encoded, which reduces subsequent encoding effort for that item. If familiarity for repeated study items decreases with the time interval between those items, it follows that participants may perform more rehearsals for stimuli repeated after a delay than for stimuli repeated immediately.

On the other hand, not all research on spacing effects in recognition fits with this voluntary rehearsal account. For example, Toppino, Kasserman, and

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[1] Although beyond the scope of the present study, it is important to note that there are alternative theories of the spacing effect that do not require deficient processing. For a more thorough review of these alternative theories, see Toppino and Gerbier (2014).

Mracek (1991) asked children of three different grade levels (preschool, first grade, and third grade) to study twice presented pictures of common objects from a picture book. The delay between repeated pictures varied from 0 to 4 items. A reliable spacing effect was observed on a later recognition memory test. Though children were instructed that this memory test would occur, it seems unlikely that these young children would have adopted different rehearsal strategies across conditions. In another study, Challis (1993) found that spacing effects depended on the orienting task used at study. Participants studied a list of words using procedures that oriented them either to graphemic features or semantic features. In contrast to the intentionality results reported by Greene (1989), Challis (1993) found a robust spacing effect despite incidental learning conditions – but only when participants oriented to semantic features of the studied words. They concluded that spacing effects in conditions that involve incidental encoding might hinge on a form of semantic priming that occurs at short spacing intervals.

Whether semantic processing is critical to the spacing effect has been the subject of some debate. Later studies found reliable spacing effects with stimuli not amenable to semantic processing, such as unfamiliar faces and non-words (Mammarella, Russo, & Avons, 2002; Russo et al., 2002, 1998; Toppino et al., 1991). These findings suggest perceptual priming may also contribute to spacing effects in recognition memory. In any case, priming that occurs with short spacing between repeated items may be accompanied by diminished attention to those repeated items (Hintzman, Block, & Summers, 1973). This diminished attention might then negatively affect the encoding of repeated items, an idea that highlights an automatic component of deficient processing that could contribute to the spacing effect.

The Repetition Decrement (RD) Effect

The RD effect reported in two recent studies (Collins, Rosner, & Milliken, 2018; Rosner et al., 2018) could in principle reflect the same diminished attention to the encoding of repeated items. The method used to measure this effect involved the presentation of prime-target word pairs in a study phase, with participants required to name just the target word. Half of the prime-target pairs were identical (repeated) words, and the other half were different (not-repeated) words. In a following recognition test phase, memory sensitivity was lower for repeated targets than for not-repeated targets (Collins et al., 2018; Rosner et al., 2018). This effect depended on how primes in these prime-target pairs were processed, occurring only when processing of the primes was poor – that is, when primes were ignored rather than named or encoded semantically (Collins et al., 2018; Rosner et al., in 2018). We concluded that the RD effect reflects diminished encoding of repeated targets during the study phase.

The notion that participants allocate fewer attentional resources to repeated than not-repeated target words fits well with the deficient processing theory of spacing effects (Cuddy & Jacoby, 1982; Hintzman, 1976; Russo et al., 2002). As such, it seemed plausible that the RD effect and spacing effects in recognition share underlying processes. To the best of our knowledge, however, no prior studies of the spacing effect have reported superior memory for an item presented just once at study than for an item presented twice at study. Moreover, spacing effect studies typically require participants to actively encode all items in a study phase, implying that participants have two opportunities to encode repeated items to a similar level of processing depth (Challis, 1993). In contrast, the procedure used to measure the RD effect involves passive ignoring of the prime in a prime-target pair (Collins et al., 2018; Rosner et al., 2018). As such, it is unclear whether the RD and spacing effects share underlying processes, and therefore also unclear whether a delay between repetitions will impact the RD effect.

The Present Study

The present study examines whether spacing between repetitions mediates the RD effect. The conceptual aim is to establish whether 'deficient processing' of repetitions constitutes a viable account of both the spacing and RD effects, and by extension to highlight the ubiquity of deficient processing effects associated with stimulus repetition. Experiment 1 was a replication of the original procedure of Rosner et al. (2018), and the results demonstrated again that immediate repetition in a study phase can negatively impact later recognition sensitivity. In Experiments 2a and 2b, prime and target words were presented in separate study blocks. In Experiment 2a, prime words were displayed with a rapid serial visual presentation (RSVP; Broadbent & Broadbent, 1987; Potter, 1976) method, whereas in Experiment 2b prime words were displayed for a longer duration and named aloud by participants. Both experiments produced benefits rather than costs of repetition, an initial indication that spacing does mediate repetition effects even for poorly encoded primes. In Experiments 3a, 3b, 4a and 4b, we examined the same issue, but with a method that carefully controlled prime encoding across methods used to measure repetition effects for immediate and spaced repetitions. The results across all experiments demonstrate that spacing between repetitions does mediate the RD effect, which supports the view that the same deficiency in processing of repetitions underlies the RD and spacing effects in recognition memory.

Experiment 1

Rosner et al. (2018; Collins et al., 2018) presented participants with two words during each trial of an incidental study phase, a green prime followed by a red target. The prime and target were either identical (repeated trials) or different (not-repeated trials), and participants were asked to name the red target aloud. The purpose of Experiment 1 was simply to replicate Experiment 1 of Rosner et al. (2018).

Method

Participants. Twenty-four participants (18 females; mean age = 19 years) from the McMaster university student pool completed the experiment for course credit or $10 CAD. All participants reported normal or corrected-to-normal vision and spoke English fluently.

Apparatus and stimuli. The experimental program was run on a Mac Mini using PsychoPy open source experimental software (v1.81.0, Peirce, 2007, 2009). The stimuli were displayed on a 24-inch BENQ LED monitor. Naming responses for the study phase were detected by a Logitech Microphone headset. Participant responses during the test phase were recorded using the keyboard. All participants were tested individually, sitting approximately 50 cm from the monitor.

During the study phase, a green prime appeared centrally followed by a red target, as shown in Figure 1. During the test phase, a single red word appeared centrally. Participants' response options in the test phase, "OLD" and "NEW", were displayed in white in the bottom left and bottom right corners of the screen, respectively. When a participant answered "OLD", the words "TYPE A" and "TYPE B", also displayed in white, replaced the words "OLD" and "NEW". In both the study and test phases, the background was black. Each word subtended approximately 0.8° of visual angle vertically and 5.9° horizontally. 360 five-letter high-frequency nouns (Thorndike & Lorge, 1944) were used in this experiment. The exact word lists can be found in Appendix A.

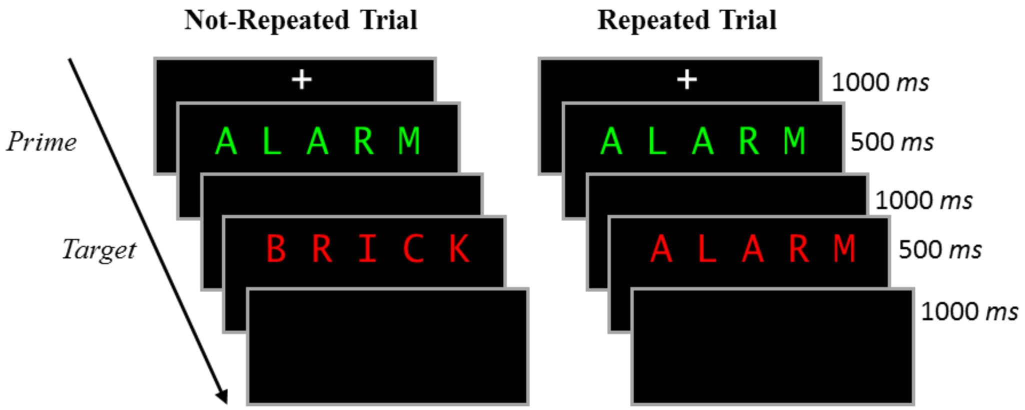

Figure 1. Depiction of stimuli in Experiment 1. The *green* word is the prime, and the *red* word is the target. In this experiment, participants simply named the target word on each trial.

Procedure. The experiment included two phases: an incidental study phase and a recognition memory test phase. Before starting the study phase, the experimenter assessed participants' comprehension of instructions by having them paraphrase the written instructions displayed on the screen. Participants then completed the study phase. A math distractor task consisting of simple arithmetic and order of operations questions followed the study phase. Participants worked on the distractor task until they had completed a set of eight math problems, or until 10 minutes had passed, whichever came first. The recognition test phase followed the math distractor task. Participants read detailed instructions for the test phase presented on screen, paraphrased those instructions for the experimenter, and then completed the recognition memory test phase itself.

In the study phase, each trial began with a fixation cross displayed for 1,000 *ms*, followed by a green prime for 500 *ms*, a blank screen for 1000 *ms*, the red target for 500 *ms*, and finally another blank screen for 1000 *ms* (see Figure 1).

The task during the study phase was to name the red target aloud as quickly and accurately as possible. Response times (RTs) were recorded from the onset of the target to the onset of a naming response, as detected by a microphone headset worn by participants. The experimenter coded participants' responses in the study phase as correct, incorrect, or spoil by pressing "1", "2", or "3" on the number pad of the keyboard. Responses were coded as incorrect if participants accidentally named the prime, or if they mispronounced the target. Responses were coded as spoils when an extraneous noise triggered the microphone (e.g., the participant sneezed, or significant ambient noise occurred). The next trial began immediately after the 1000 *ms* blank interval that followed target offset.

In the surprise recognition memory test, each trial consisted of a 1,000 *ms* fixation cross followed by a single word. Participants were to decide whether the word was a target item from the earlier study phase or a new, previously unseen lure. They indicated their "old" and "new" decisions via a keyboard response; "A" for "old" and "L" for "new". For "old" responses, participants were also required to make a remember/know classification, once again via keyboard press. The test phase instructions defined the difference between "remembering" and "knowing" in accord with the definitions provided by Rajaram (1993). These "remember" and "know" judgments were labelled "Type A" and "Type B", and mapped to the "A" and "L" keys, respectively. Remember/know data were collected in all experiments for exploratory purposes. These data are presented in Appendix B for the interest of the reader but are not discussed in depth here.

Design. On half of the study phase trials, the green prime and red target were the same (repeated targets). On the other half of study phase trials, the green prime and red target were different (not-repeated targets). The 360 words used in the experiment were randomly divided into six lists of 60 words (see Appendix A). For each participant, three of the word lists were assigned to "old" trials, and three of the word lists were assigned to "new" trials. The assignment of word lists to each role was counterbalanced across participants. For "old" trials, one list was assigned to the not-repeated prime role, another list to the not-repeated target role, and a third list to the repeated prime/target role. A similar assignment of lists to roles occurred for the 'new' trials, although in practice the not-repeated prime items were not actually presented to participants. We counterbalanced the lists such that each item appeared in each of the possible six roles in the design an equal number of times. Overall, 60 repeated trials were randomly intermixed with 60 not-repeated trials in the study phase, and 120 old targets were randomly intermixed with 120 previously unseen lures in the recognition test phase.

Results

Naming phase. RTs lower than 200 ms and RTs for spoils and incorrect trials (1.8% of observations) were excluded from all analyses. The remaining RTs were submitted to an outlier elimination procedure (Van Selst & Jolicoeur, 1994) that excluded an additional 1.9% of trials from further analysis. Mean RTs for each repetition condition (repeated/not-repeated) were computed from the remaining observations. Table 1 lists the mean RTs for each condition, collapsed across participants. These mean RTs were submitted to a paired sample *t*-test. Responses were faster for repeated targets (*M* = 500 *ms*, *SD* = 86 *ms*) than for not-repeated targets (*M* = 556 *ms*, *SD* = 98 *ms*), *t*(23) = 5.80, *p* < .001, *d* = 0.61.

Table 1 Mean response times (*ms*) and error rates for naming target words in the study phase

		Block 1		Block 2	
Exp	Prime Task	Not-Repeated	Repeated	Not-Repeated	Repeated
1	Ignore	556	500		
2a	RSVP			527	522
2b	Name			518	495
3a	Ignore	507	474	501	494
3b	Name	543	506	525	512
4a	Ignore	524	495	526	518
4b	Ignore	525	488	512	508

Test phase. Target words coded as an error or spoil in the study phase were excluded from the analysis of the test phase in this and all following experiments. The primary dependent variable for all recognition phase analyses in the current study was the proportion of “old” responses. Figure 2 displays mean hit and false alarm rates collapsed across participants.

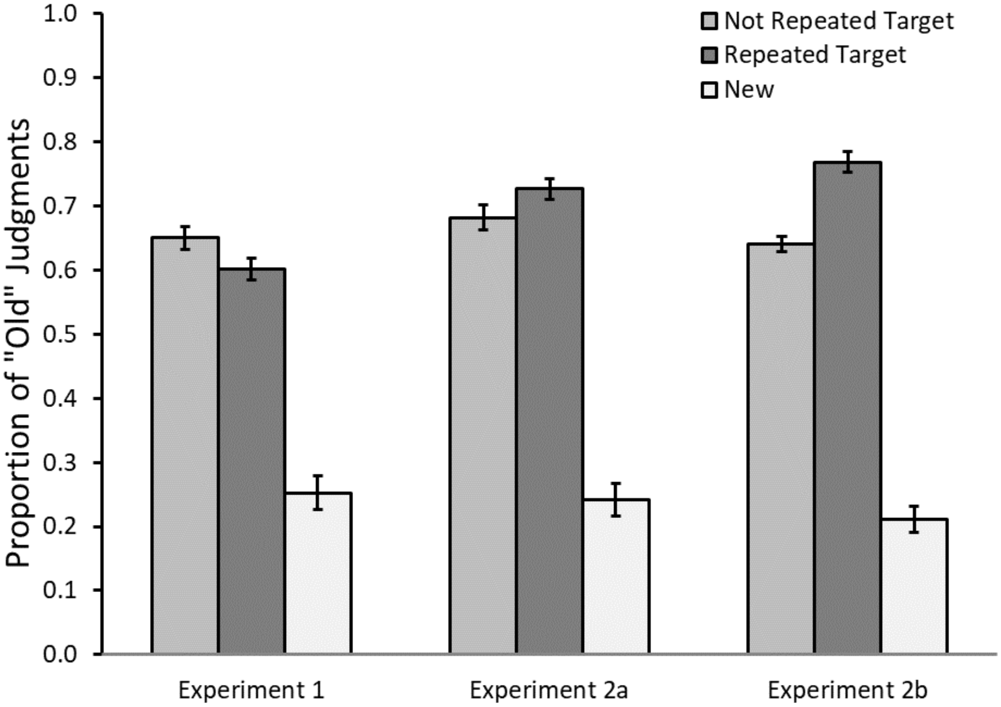

Figure 2. Mean proportion of "old" judgments in Experiments 1, 2a, and 2b collapsed across participants. Error bars represent within-subject standard errors (Cousineau, 2005; Morey, 2008)

Two paired sample *t*-tests were conducted to assess recognition memory performance. The first analysis compared the hit rate collapsed across the two repetition conditions (repeated/not-repeated) to the false alarm rate simply to assess participants' ability to distinguish old from new items. Indeed, hit rates (*M* = .626, *SD* = .159) were higher than false alarm rates (*M* = .252, *SD* = .162), *t*(23) = 11.62, *p* < .001, *d* = 2.33. The second analysis compared the hit rates for the not-repeated and repeated targets. The comparison revealed that hit rates were higher for not-repeated targets (*M* = .650, *SD* = .157) than for repeated targets (*M* = .602, *SD* = .174), *t*(23) = 2.54, *p* = .019, *d* = 0.29.

Discussion

The present experiment constitutes a successful replication of Experiment 1 from the Rosner et al. (2018) study. A significant RD effect was observed; that is, recognition sensitivity was higher for not-repeated items than for repeated items.

Experiments 2a and 2b

We now turn to the relation between the RD effect and the spacing effect (Ebbinghaus, 1885). Rosner et al. (2018) took a first step to addressing this issue using a procedure that placed an intervening item between the prime and target on each trial in the study phase. Superior recognition for not-repeated targets was observed with this method as well, demonstrating that repeated prime-target pairs do not have to be presented in immediate sequence for the RD effect to occur. At the same time, the interval between repetitions remained quite short in that experiment (i.e., a few seconds). As the spacing effect may hinge on spacing disrupting memory of the first of two repeated events (Cuddy & Jacoby, 1982, Russo et al., 1998), a longer interval between repeated items might be necessary for recognition to benefit from repetition.

We tested this idea in Experiments 2a and 2b by presenting prime and target words in separate study blocks. The first study block (block 1) consisted entirely of green prime words. The second study block (block 2) consisted entirely of red target words. Half of the words in block 2 were identical to previously studied green primes from block 1, whereas the other half were new words not previously seen in the experiment. As in Experiment 1, participants named the red target words aloud. Two different methods were used for presentation of the primes in block 1. In Experiment 2a, we used an RSVP procedure (Broadbent & Broadbent, 1987; Potter, 1976) to limit attention to the green primes. In Experiment 2b, participants named the green primes aloud. This prime encoding manipulation (RSVP vs read) across Experiments 2a and 2b addressed whether memory for words repeated in separate blocks hinges on the encoding of primes in block 1. We hypothesised that the RSVP method in Experiment 2a would lead to poor encoding of primes, perhaps comparably poor to the ignored primes in Experiment 1, and undoubtedly inferior to the named primes in Experiment 2b.

Method

Participants. Twenty-four participants completed Experiment 2a (15 females; mean age = 19 years), and a separate group of 24 participants completed Experiment 2b (17 females; mean age = 19 years). Participants were recruited from the McMaster University student pool and completed the experiment for course credit or a cash payment of $10 CAD. All participants had normal or corrected-to-normal vision and spoke fluent English.

Apparatus and stimuli. The apparatus and stimuli in Experiments 2a and 2b were identical to those in Experiment 1.

Procedure. Experiments 2a and 2b again consisted of two phases: an incidental study phase followed by a test phase. The test phase was identical to

Experiment 1. The study phase consisted of two blocks of trials, with primes presented in block 1 and targets presented in block 2. The primes in block 1 were presented in green, and the targets in block 2 were presented in red. Half of the targets in block 2 were the same words presented in block 1, while the other half of the targets were new words not previously seen in block 1. In total, 60 primes were presented in block 1, and 120 targets were presented in block 2.

The procedure for block 1 differed between Experiments 2a and 2b. In Experiment 2a, the primes in block 1 were presented with an RSVP-like procedure (Broadbent & Broadbent, 1987; Potter, 1976). The block of trials began with a central fixation cross displayed for 1,000 *ms*, after which the RSVP sequence began. Each trial in the RSVP sequence consisted of a green prime displayed centrally for 200 *ms*, followed by a blank screen for 300 *ms*. Participants were instructed to attend to and read the green primes silently. The experimenter coded participants’ responses as an error if they read the word aloud. In Experiment 2b, the primes in block 1 were presented in a slower sequence that allowed an overt naming response for each word. Each trial in block 1 consisted of a central fixation cross displayed for 1,000 *ms*, followed by a green prime for 500 *ms*, and finally a blank screen for 1,000 *ms*. Participants were asked to name aloud each word as quickly and accurately as possible. The experimenter coded as errors any pronunciation errors or failures to read the word aloud.

The procedure for block 2 was identical for Experiments 2a and 2b. Participants simply named the red target words aloud. On each trial, participants saw a central fixation cross for 1,000 *ms*, followed by a red target word for 500 *ms*, and finally a blank screen for 1,000 *ms*. As in Experiment 1, RTs were recorded from the onset of the target word to the onset of participant's response. The experimenter coded responses as correct, incorrect, or spoils where applicable.

The counterbalancing scheme used for these experiments was similar to Experiment 1. Again, six lists of 60 words were used, with three lists assigned to be 'old' words and three lists assigned to be 'new' words for any given participant. For the 'old' items presented in both the study and test phases, one list was assigned to the role of repeated target (presented in both block 1 and block 2), and another list was assigned to the role of not-repeated target (presented only in block 2). For the 'new' items presented in the test phase only, two of the three lists were presented to each participant in the test phase. Across participants, lists were counterbalanced so that each word appeared equally often as an 'old' and 'new' item, and as a repeated and not-repeated target. The test phase included a total of 120 old words (60 repeated and 60 not-repeated) and 120 new words.

Results

Naming phase. Block 2 naming RTs lower than 200 *ms* were excluded from analysis (3.8% of trials in Experiment 2a; 7.3% of trials in Experiment 2b).

The remaining RTs were submitted to the same outlier analysis as in Experiment 1, which removed a further 1.9% of trials from Experiment 2a and 1.8% of trials from Experiment 2b. Mean RTs were computed from the remaining observations and submitted to a paired sample *t*-test that compared repeated and not-repeated conditions. Mean RTs collapsed across participants for these two conditions are displayed in Table 1. In Experiment 2a, RTs were not significantly different for not-repeated targets (*M* = 527 *ms*, *SD* = 80 *ms*) and repeated targets (*M* = 522 *ms*, *SD* = 90 *ms*), *p* = .443. In Experiment 2b, RTs were significantly slower for not-repeated targets (*M* = 518 *ms*, SD = *88 ms*) than for repeated targets (*M* = 495 *ms*, *SD* = 65 *ms*), *t*(23) = 3.57, *p* = .002, *d* = 0.30.

Test phase. Only target words responded to correctly in block 1 and block 2 were included in the analysis. Figure 2 displays mean hit and false alarm rates collapsed across participants. For both Experiments 2a and 2b, two paired sample *t*-tests were conducted. The first analysis compared the overall hit and false alarm rates to confirm that recognition performance was above chance. The second analysis compared the hit rates for not-repeated and repeated targets to assess the effect of repetition on recognition performance.

Experiment 2a. The analysis of hits relative to false alarms revealed a significant effect, *t*(23) = 15.05, *p* < .001, *d* = 3.55. As expected, the hit rate (*M* = .704, *SD* = .130) was higher than the false alarm rate (*M* = .242, *SD* = .130). The analysis of hit rates in the two repetition conditions also revealed a significant effect, *t*(23) = 2.12, *p* = .045, *d* = 0.32. Despite limited attention to rapidly presented primes in block 1, the hit rate was higher for repeated targets (*M* = .727, *SD* = .136) than for not-repeated targets (*M* = .682, *SD* = .144).

Experiment 2b. The analysis of hits relative to false alarms again revealed a significant effect, *t*(23) = 19.57, *p* < .001, *d* = 3.32, with a higher hit rate (*M* = .704, *SD* = .161) than false alarm rate (*M* = .211, *SD* = .136). The analysis of the two repetition conditions also revealed a significant effect, *t*(23) = 7.87, *p* < .001, *d* = 0.77, with a higher hit rate for repeated targets (*M* = .768, *SD* = .154) than for not-repeated targets (*M* = .640, *SD* = .178). Naming words aloud in block 1 resulted in a robust recognition benefit for repeated targets.

Discussion

In both Experiments 2a and 2b, repetition improved recognition memory. This result was a robust one in Experiment 2b, but also statistically significant in Experiment 2a, in which rapid serial presentation limited attention to primes in block 1. We conclude that even poorly encoded primes in block 1 that are repeated in block 2 improve recognition memory relative to items seen for the first time in block 2.

Experiments 3a and 3b

The results of Experiments 2a and 2b demonstrate that a word presented once in block 1 and repeated later in block 2 is recognised better than a word presented just once in block 2. Further, this result holds both for words read aloud in block 1 (Experiment 2b) and for words identified covertly with rapid serial presentation in block 1 (Experiment 2a). These results suggest that the RD effect observed in Experiment 1 may be limited to immediate repetition, whereas longer intervals between repetition benefit recognition.

However, the different repetition effects across experiments described above could be related to differences in the encoding of primes across experiments. To address this issue in the present experiments, we equated the processing of primes for immediate and spaced repetition of targets using a hybrid of the procedures used in Experiments 1, 2a, and 2b. As in Experiments 2a and 2b, the study phase consisted of two separate blocks, and block 2 included a mix of repeated and not-repeated words to be named aloud. In contrast to Experiments 2a and 2b, block 1 used a procedure similar to the study phase of Experiment 1; that is, each trial in block 1 consisted of a prime-target pair and participants named the target aloud. Critically, this design allowed us to compare the repetition effect for repeated targets that immediately followed ignored primes in block 1 with the repetition effect for repeated targets in block 2 that appeared about 10 minutes after their corresponding ignored primes were presented in block 1.

We conducted two experiments with this new design. In Experiment 3a participants ignored the primes in block 1, whereas in Experiment 3b participants named the primes aloud in block 1. Given the results of prior studies (Collins et al., 2018; Rosner et al., 2018), we predicted an RD effect for immediate repetition in Experiment 3a, and a repetition benefit for immediate repetition in Experiment 3b. The more critical issue was whether performance for repeated trials (relative to not-repeated trials) would improve from block 1 to block 2—in line with the spacing effect.

Method

Participants. Thirty-six participants completed Experiment 3a (27 females; mean age = 19 years), and an additional 36 participants completed Experiment 3b (31 females; mean age = 19 years). Participants were recruited from the McMaster University student pool and completed the experiment for course credit or a cash payment of $10 CAD. All participants had normal or corrected-to-normal vision and spoke fluent English.

Apparatus and Stimulus. The apparatus and stimuli used in Experiments 3a and 3b were identical to those used in prior experiments with one exception. At test, words were displayed in white rather than red.

Procedure. As in Experiments 2a and 2b, there is an apparent discrepancy between the overall hit rate reported in this analysis and those reported in Figure 4 and the analysis of repetition effects. This is because the overall hit rate includes recognition memory for both the not-repeated primes (i.e., words appearing only once as a prime) and the not-repeated targets that were paired with the primes to be repeated in block 2. This is also true for the overall hit rate analysis in Experiments 3b, 4a, and 4b. A complete record of "old" response rates and associated standard deviation for all item types can be found in Appendix C. The study phase had two blocks (see Figure 3). In block 1, the stimuli were identical to Experiment 1, with a green prime followed by a red target on each trial. In

Experiment 3a, participants ignored the green prime and named the red target aloud on each trial. In Experiment 3b, participants named both the green prime and red target aloud. Study block 2 in both Experiments 3a and 3b were identical to that in Experiments 2a and 2b. Participants simply named a series of red target words aloud. For both study blocks, RTs were recorded from onset of the target stimulus to onset of the participant's naming response, and the experimenter coded each naming response as correct, incorrect, or a spoil. The approximate time between the beginning of block 1 and the beginning of block 2 was ten minutes. Following the study phase, participants completed a math distractor task followed by the test phase. The test phase was identical to that used in previous experiments.

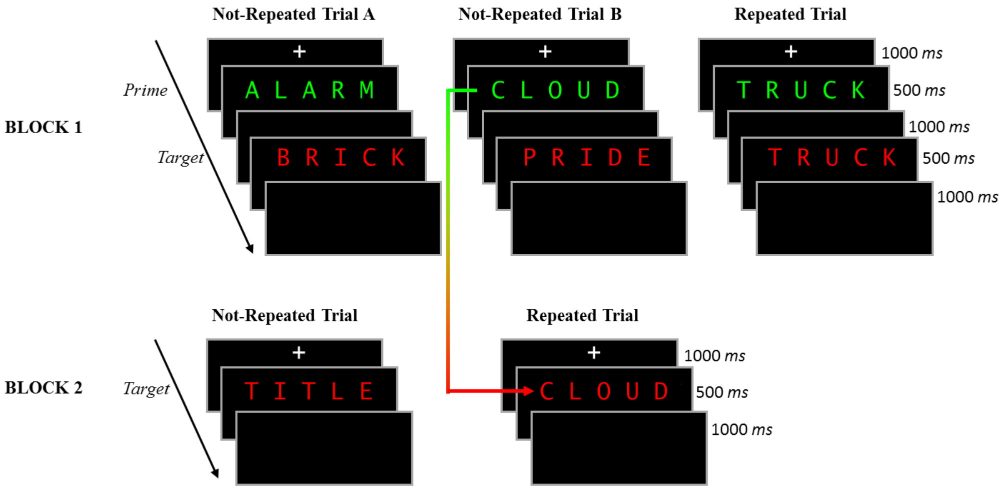

Figure 3. Depiction of stimuli in Experiments 3a and 3b. The *green* words are primes, and the *red* words are targets. In this experiment, participants always named target words aloud in each block. Instructions for the green prime word in block 1 varied aross experiments; ignore in Experiment 3a, read in Experiment 3b.

Design. Although the set of words used was identical to previous experiments, significant changes to the list structure were necessary to accommodate the new design. Rather than six lists of 60 words, we assigned the 360 words to nine lists of 40 words. For any given participant, six of these word lists were "old" items, and three were "new" items in the test phase. We further subdivided the "old" items into six roles, one for each of the six lists as follows. Two lists served as not-repeated primes in block 1, two lists served as not-repeated targets in block 1, one list served as repeated primes and targets in block 1, one list served as not-repeated targets in block 2, and one list served as repeated targets in block 2. The key property of this design is that one of the lists assigned to not-repeated primes for block 1 is also assigned to repeated targets for block 2, which keeps the total number of required 'old' lists to six. We counterbalanced the order and assignment of lists such that each list occurred an equal number of times in each 'old' role. The three remaining lists for any particular participant were used for new items. Together, this assignment of lists to conditions resulted in 120 block 1 study trials (80 not-repeated, 40 repeated), and 80 block 2 study trials (40 not-repeated, 40 repeated). All lists appeared at test, for a total of 240 "old" trials and 120 "new" trials.

Also noteworthy is that the presentation order of not-repeated primes in block 1 was identical to the order that those same items appeared as repeated targets in block 2, although in block 2 these items were randomly intermixed with a set of not-repeated (new) targets. This procedure was adopted to preserve a consistent temporal interval between the presentation of these primes and repeated targets, although following experiments (Experiments 4a and 4b) later revealed that this constraint did not impact the results.

Results

Naming phase. As in earlier experiments, only RTs for correctly named targets greater than 200 *ms* were included in the analysis. This criterion eliminated 4.5% of trials in Experiment 3a and 4.3% of trials in Experiment 3b. An additional outlier procedure removed a further 2.9% of trials in Experiment 3a and 2.6% of trials in Experiment 3b (Van Selst & Jolicoeur, 1994). Mean RTs were computed from the remaining observations and were submitted to repeated measures ANOVA that treated block (1/2) and repetition (not-repeated/repeated) as factors. Mean RTs collapsed across participants are displayed in Table 1.

Experiment 3a. The analysis revealed a significant main effect of repetition, $F(1,35) = 20.90$, $p < .001$, $\eta_p^2 = .374$, that was qualified by a significant interaction between block and repetition, $F(1,35) = 12.54$, $p = .001$, $\eta_p^2 = .264$. Separate analyses of the repetition effect for the two blocks revealed that responses were faster for repeated targets ($M = 474$ *ms*, $SD = 83$ *ms*) than for not-repeated targets ($M = 507$ *ms*, $SD = 76$ *ms*) in block 1, $t(35) = 4.79$, $p < .001$, $d = 0.80$, whereas a trend in the direction of faster responses for repeated targets ($M = 493$ *ms*, $SD = 79$ *ms*) than for not-repeated targets ($M = 501$ *ms*, $SD = 80$ *ms*) only approached significance in block 2, $t(35) = 1.77$, $p = .085$, $d = 0.09$.

Experiment 3b. The analysis revealed a significant main effect of repetition, $F(1,35) = 35.56$, $p < .001$, $\eta_p^2 = .504$, that was again qualified by a significant interaction between block and repetition, $F(1,35) = 7.55$, $p = .009$, $\eta_p^2 = .177$. In block 1, responses were faster for repeated targets ($M = 507$ *ms*, $SD = 77$ *ms*) than for not-repeated targets ($M = 544$ *ms*, $SD = 75$ *ms*), $t(35) = 6.06$, $p < .001$, $d = 0.49$. In block 2, responses were also faster for repeated targets ($M = 512$ *ms*, $SD = 73$ *ms*) than for not-repeated targets ($M = 525$ *ms*, $SD = 70$ *ms*), $t(35) = 2.28$, $p = .029$, $d = 0.19$. As in Experiment 3a, these results indicate that the interaction was driven by a larger repetition effect in block 1 than block 2.

Test phase. The inclusion criteria and dependent variables for Experiments 3a and 3b were identical to Experiments 2a and 2b. Note that for block 1 analyses, only the not-repeated trials that were not used to create repeated trials in block 2 were included. Figure 4 displays the mean hit and false alarm rates collapsed across participants. For each of Experiments 3a and 3b, we conducted two analyses. For the first analysis, we compared hit and false alarm rates collapsed across conditions to confirm that memory performance was better than chance. In the second analysis, hit rates were submitted to a repeated measures ANOVA that treated block (1/2) and repetition (not-repeated/repeated) as within-subject factors.

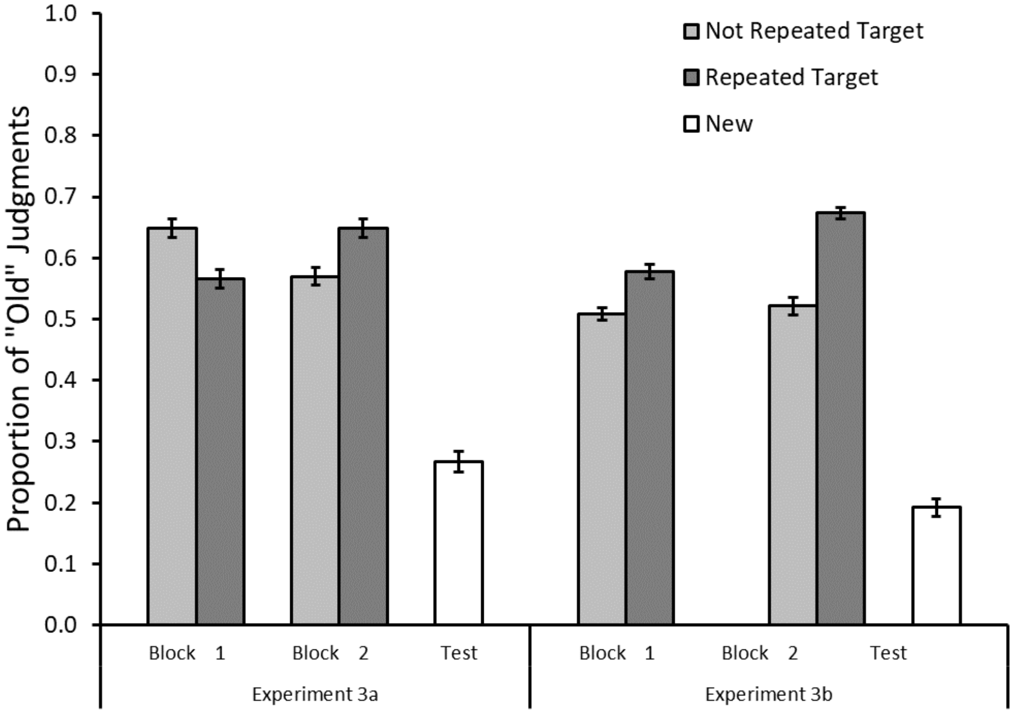

Figure 4. Mean proportion of "old" judgments, collapsed across participants. Error bars represent within-subject standard errors (Cousineau, 2005; Morey, 2008).

Experiment 3a. The hit rate (M = .553, SD = .137)[2] was higher than the false alarm rate (M = .192, SD = .110), $t(23) = 23.54$, $p < .001$, d = 2.14, indicating that participants were able to recognize items with better than chance level accuracy. In the analysis of hit rates, there was a significant interaction between block and repetition, $F(1,35) = 40.42$, $p < .001$, $\eta_p^2 = .536$. For block 1, the immediate repetition condition, the hit rate was higher for not-repeated targets (M = .648, SD = .175) than for repeated targets (M = .566, SD = .169), $t(35)$ =

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[2] words appearing only once as a prime) and the not-repeated targets that were paired with the primes to be repeated in block 2. This is also true for the overall hit rate analysis in Experiments 3b, 4a, and 4b. A complete record of "old" response rates and associated standard deviation for all item types can be found in Appendix C.

4.20, *p* < .001, *d* = 0.48. For block 2, the spaced repetition condition, the hit rate was higher for repeated targets (*M* = .648, *SD* = .162) than for not-repeated targets (*M* = .570, *SD* = .166), *t*(35) = 3.88, *p* < .001, *d* = 0.48.

Experiment 3b. The hit rate (*M* = .573, *SD* = .151) was again significantly higher than the false alarm rate (*M* = .266, *SD* = .135), *t*(35) = 16.57, *p* < .001, *d* = 2.92. In the analysis of hit rates, there was a significant main effect of block, *F*(1,35) = 25.43, *p* < .001, η_p^2 = .421, with higher hit rates for block 2 (*M* = .598, *SD* = .158) than for block 1 (*M* = .543, *SD* = .149). There was also a significant main effect of repetition, *F*(1,35) = 87.75, *p* < .001, η_p^2 = .715, with higher hit rates for repeated targets (*M* = .626, *SD* = .151) than for not-repeated targets (*M* = .515, *SD* = .140). Finally, the interaction between block and repetition was also significant, *F*(1,35) = 13.05, *p* = .001, η_p^2 = .272. The repetition effect was significant both for both block 1, *t*(35) = 4.31, *p* < .001, *d* = 0.48, and block 2, *t*(35) = 9.05, *p* < .001, *d* = 1.09, and in both cases the hit rate was higher for repeated targets than for not-repeated targets. The source of the interaction is clear in Figure 3; the repetition effect was larger for block 2 than for block 1.

Discussion

The goal of Experiments 3a and 3b was to compare the effects of immediate and spaced repetition using a design that ensured processing of primes did not differ for the immediate and spaced repetition conditions. In Experiment 3a, where participants named only the target words in block 1, an RD effect was observed in block 1 (immediate repetition), whereas recognition was better for repeated than not-repeated targets in block 2 (spaced repetition). This result is consistent with our prior studies that focused on immediate repetition (Collins et al., 2018; Rosner et al., 2018), and consistent also with the view that similar processes drive the RD effect and the spacing effect. In Experiment 3b, where participants named aloud the primes and targets in block 1, recognition of not-repeated targets was inferior to that for repeated targets in both block 1 and block 2, with this effect being larger in block 2 than block 1. This result is also consistent with our prior studies that focused on immediate repetition (Collins et al., 2018; Rosner et al., 2018), and compatible with the view that processes responsible for the spacing effect mediate the change in repetition effect for immediate and spaced repetitions observed here.

Experiments 4a and 4b

An idiosyncrasy in the design of Experiments 3a and 3b is that the relative order of repeated targets in block 2 was preserved from their order of presentation in block 1. In other words, if a repeated target appeared near the beginning of block 1, it would also appear near the beginning of block 2, and so forth for all serial positions. We used this design so that the temporal interval separating repetitions was similar for all items. We conducted Experiments 4a and 4b to evaluate whether this idiosyncrasy in our design contributed to the effects observed in Experiments 3a and 3b. In Experiment 4a, we replicated the procedure of Experiment 3a, preserving the relative presentation order of repeated targets between blocks 1 and 2. In Experiment 4b, we eliminated this constraint on order of presentation, and instead presented repeated items (randomly intermixed with not-repeated items) in random order in block 2.

Method

Participants. Thirty-six participants completed Experiment 4a (30 females; mean age = 19 years), and a separate group of 36 participants completed Experiment 4b (31 females; mean age = 19 years). Participants were recruited from the McMaster University student pool and completed the experiment for course credit or a cash payment of $10 CAD. All participants had normal or corrected-to-normal vision and spoke fluent English.

Apparatus, stimulus, and procedure. The apparatus, stimuli, and procedure used in Experiments 4a and 4b were identical to Experiment 3a.

Design. The design of Experiment 4a was identical to Experiment 3a. The design of Experiment 4b differed from Experiment 4a in just one way. In Experiment 4a (and in Experiments 3a and 3b), the presentation order of repeated targets in block 2 was preserved relative to the presentation order of their matching primes in block 1. For example, if “COUCH” appeared as a prime before “PRIDE” appeared as a prime in block 1, then “COUCH” also appeared as a repeated target before “PRIDE” appeared as a repeated target in block 2. In Experiment 4b, we eliminated this constraint on presentation order of repeated items in block 2, instead randomising the order of repeated targets in block 2 without constraint.

Results

Naming phase. As in previous experiments, RTs for correctly named targets greater than 200 *ms* were included in the analysis. This inclusion criterion eliminated 6.9% of trials in Experiment 4a and 6.0% of trials in Experiment 4b. A supplementary outlier procedure removed an additional 3.2% of trials in Experiment 4a and 2.2% of trials in Experiment 4b (Van Selst & Jolicoeur, 1994). Mean RTs were computed from the remaining observations and were submitted to a repeated measures ANOVA that treated block (1/2) and repetition (not-repeated/repeated) as factors.

Experiment 4a. There was a significant main effect of repetition, $F(1,35) = 23.49$, $p < .001$, $\eta_p^2 = .402$, that was qualified by a significant interaction between block and repetition, $F(1,35) = 7.49$, $p = .012$, $\eta_p^2 = .168$. In block 1, participants responded faster to repeated targets ($M = 495$ *ms*, $SD = 97$ *ms*) than to not-repeated targets ($M = 524$ *ms*, $SD = 93$ *ms*), $t(35) = 7.49$, $p < .001$, $d = 0.31$. In block 2, there was a trend toward faster RTs for repeated targets ($M = 493$ *ms*, $SD = 79$ *ms*) than for not-repeated targets ($M = 501$ *ms*, $SD = 80$ *ms*), however this difference was not significant, $t(35) = 1.42$, $p = .164$, $d = 0.09$.

Experiment 4b. There was a significant main effect of repetition, $F(1,35) = 43.32$, $p < .001$, $\eta_p^2 = .553$, that was qualified by a significant interaction between block and repetition, $F(1,35) = 14.87$, $p < .001$, $\eta_p^2 = .298$. In block 1, participants responded faster to repeated targets ($M = 488$ *ms*, $SD = 71$ *ms*) than to not-repeated targets ($M = 525$ *ms*, $SD = 76$ *ms*), $t(35) = 7.18$, $p < .001$, $d = 0.50$.

As in Experiment 4a, this difference was not significant in block 2, $t(35) = 0.79$, $p = .434$, $d = .05$ ($M = 508$ *ms*, $SD = 93$ *ms* for repeated trials; $M = 512$ *ms*, $SD = 86$ *ms* for not-repeated trials).

Test phase. The inclusion criteria and dependent variables for Experiments 4a and 4b were identical to Experiments 3a and 3b. Figure 5 displays the mean hit and false alarm rates collapsed across participants.

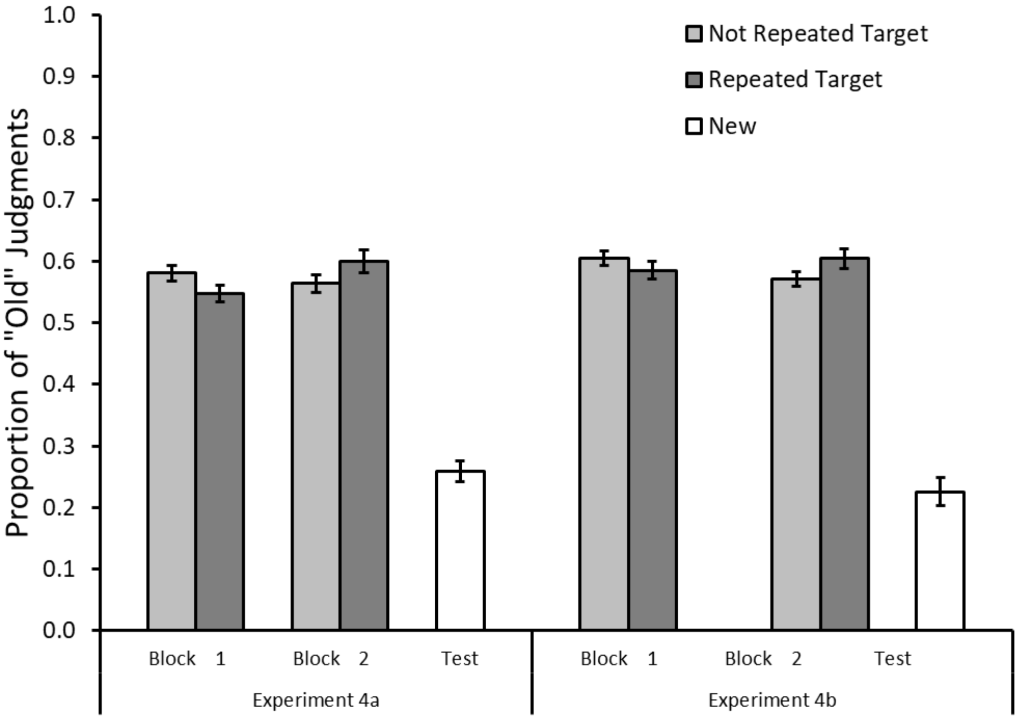

Figure 5. Mean proportion of "old" judgments, collapsed across participants. Error bars represent within-subject standard errors (Cousineau, 2005; Morey, 2008).

Experiment 4a. The overall hit rate ($M = .540$, $SD = .140$) was higher than the false alarm rate ($M = .258$, $SD = .142$), $t(35) = 15.48$, $p < .001$, $d = 2.00$, indicating that participants could recognize items with better than chance level accuracy. The analysis of hit rates revealed a significant interaction between block and repetition, *F*(1,35) = 5.68, *p* = .023, η_p^2 = .140. In block 1, the repetition effect for immediate repetitions was not significant, *t*(35) = 1.69, *p* = .100, *d* = 0.21, though the trend was similar to that reported in Experiment 3a. Hit rates were higher for not-repeated targets (*M* = .581, *SD* = .165) than repeated targets (*M* = .548, *SD* = .143). In block 2, the hit rate for repeated targets (*M* = .600, *SD* = .167) was numerically higher than for not-repeated targets (*M* = .564, *SD* = .160), though this effect again only approached significance, *t*(35) = 1.65, *p* = .108, *d* = 0.22.

Experiment 4b. The overall hit rate (*M* = .553, *SD* = .168) was higher than the false alarm rate (*M* = .226, *SD* = .148), *t*(35) = 181.29, *p* < .001, *d* = 2.06, indicating again that recognition was better than chance level accuracy. The analysis of hit rates revealed a significant interaction between block and repetition, *F*(1,35) = 5.04, *p* = .031, η_p^2 = .126. For block 1, hit rates were numerically higher for not-repeated target words (*M* = .605, *SD* = .188) than repeated target words (*M* = .585, *SD* = .188), though this difference was not significant, *t*(35) = 1.10, *p* = .277, *d* = 0.10. In block 2, hit rates were higher for repeated targets (*M* = .605, *SD* = .189) than for not-repeated targets (*M* = .571, *SD* = .176), *t*(35) = 2.09, *p* = .044 , *d* = 0.19.

Combined Analysis. As the designs of Experiments 4a and 4b were very similar, an analysis of hit rates that included experiment as a between-subjects variable was also conducted. Only the interaction between block and repetition was significant, *F*(1,70) = 10.67, *p* = .002, η_p^2 = .132. The repetition effects were subsequently analyzed separately for the two blocks. In block 1, the hit rate for not-repeated targets (*M* = .593, *SD* = .189) was higher than for repeated targets (*M* = .567, *SD* = .167), *t*(71) = 2.00, *p* = .049, *d* = 0.15. In contrast, in block 2, the hit rate for repeated targets (*M* = .602, *SD* = .177) was higher than for not-repeated targets (*M* = .567, *SD* = .167), *t*(71) = 2.58, *p* = .012, *d* = 0.20.

Discussion

The results in Experiments 4a and 4b were similar to those in Experiment 3a. An RD effect was observed for immediate repetitions in block 1, and the opposite effect was observed for spaced repetitions in block 2. Together, these results are consistent with the view that spacing mediates the influence of repetition on recognition memory, as in the well-known spacing effect.

General Discussion

The primary aim of the present study was to determine whether the processes driving the RD effect are related to those driving the spacing effect in recognition memory. In Experiment 1, the RD effect for immediate repetitions reported in our prior studies was replicated (Collins et al., 2018; Rosner et al., 2018). In Experiments 2a and 2b, spaced repetition of primes and targets presented in separate blocks produced the opposite result, a repetition benefit, both with RSVP primes in block 1 (Experiment 2a), and with longer duration primes that were named in block 1 (Experiment 2b). These results provided preliminary evidence that spacing mediates the influence of repetition on recognition memory as measured with our method. The hybrid procedure introduced in Experiments 3a and 3b allowed us to compare immediate and spaced repetition effects for primes that were encoded identically in the study phase. Primes were ignored immediately prior to naming a target in Experiment 3a, and primes were named immediately prior to naming a target in Experiment 3b. In Experiment 3a, an RD effect was observed for immediate repetition and a repetition benefit was observed for spaced repetition. In Experiment 3b, a repetition benefit was observed for both immediate and spaced repetitions, although this effect was larger for spaced than immediate repetitions. The results of Experiments 4a and 4b mirrored those of Experiment 3a; an RD effect was observed for immediate repetition, and a repetition benefit was observed for spaced repetition.

Together, the results of the present study indicate that the RD effect is robust and replicable, and confirms a that the RD effect occurs for ignored primes but not for attended primes (Collins et al., 2018; Rosner et al., 2018). Most important, the present study demonstrates that temporal spacing mediates the RD effect. Whereas immediate repetition produced an RD effect, spaced repetition produced the opposite effect. The dependence of the RD effect on temporal spacing is crucial to understanding why it occurs. Indeed, this result suggests that the RD effect is mediated by the same processes that underlie the spacing effect in recognition.

The RD Effect and Deficient Processing Theories

Greene (1989) proposed a variant of deficient processing theory in which spacing effects in recognition tests result from decreased voluntary rehearsal of repeated stimuli. According to this view, the familiarity of repetitions that are spaced close together lead participants not to engage in effortful encoding (e.g., rehearsal) of repeated items. We suggest that the recognition effects in the present study are unlikely to result from voluntary strategies for two reasons. First, our experiments utilised an incidental study procedure, and there is no obvious reason voluntary rehearsal would play a role in a study phase that has no requirement to remember. Second, the long list length and rapid presentation rate meant participants had little time to engage in voluntary rehearsal. To be clear, we are not suggesting that voluntary rehearsal never contributes to spacing effects in recognition; rather, we are concluding that voluntary rehearsal does not account for the influence of spacing on repetition effects observed here.

An alternative variant of deficient processing theory is that spacing effects in recognition are related to a transient but automatic decrease in encoding for primed stimulus representations (Challis, 1993; Russo et al., 1998; Toppino et al., 1991; see also Rosner & Milliken, under review). Given the shortcomings of the voluntary rehearsal account, the idea that priming leads to automatically diminished encoding seems a good starting point to develop an account of the present results. The specific nature of the primed representations that trigger deficient processing is an open issue. Semantic priming has been implicated in prior studies (Challis, 1993; Hintzman, 1976; Hintzman et al., 1973; Russo et al., 1998), but spacing effects have also been observed in perceptual priming experiments (Mammarella et al., 2002; Russo et al., 2002, 1998; Toppino et al., 1991). The results of our studies do not allow us to arbitrate whether perceptual or conceptual representations are particularly important.

However, the results of the present study do offer three important contributions to the spacing effect literature. First, the results confirm that spacing does mediate the influence of repetition on recognition with incidental study procedures (Experiments 3a/3b, 4a/4b). This finding is noteworthy in that the absence of a spacing effect with incidental study procedures had previously been cited as justification for voluntary variants of the deficient processing theory (Greene, 1989; but see Challis, 1993). Second, to our knowledge, the present results constitute the first observation that spacing mediates the influence of repetition on recognition with a method in which repeated items match a previously ignored item (Experiments 3a, 4a/4b). Third, the strong dependence of the repetition effects reported here on temporal spacing suggests that these effects are influenced by the same automatic processes that mediate the spacing effect.

The RD Effect and the New Theory of Disuse

Although the deficient processing theory of spacing effects in recognition can readily explain the poor encoding of repeated targets, it is not obvious how this theory would account for the RD effect. Even if priming resulted in relatively poor encoding, intuition suggests the combined representation of the prime-target pair in memory should be at least as robust as the representation of a single not-repeated target word. The new theory of disuse (NTD; Bjork & Bjork, 1992, 2006) offers a convenient alternative framework for understanding the RD effect.

The NTD describes memory as possessing two strengths: storage strength and retrieval strength (Bjork, 1999; Bjork & Bjork, 1992, 2006). Storage strength represents how well an item is learned. Retrieval strength represents how accessible an item is in memory. Both storage strength and retrieval strength increase monotonically with repeated study. Unlike storage strength, however, retrieval strength decays as a function of time. These memorial properties work in opposition, with retrieval strength informing the need for additional encoding. If retrieval strength is low, encoding is necessary, and storage strength increases. If retrieval strength is high, encoding is unnecessary, and storage strength does not increase.

This interaction is key to explaining both the spacing and RD effect. The spacing effect occurs because retrieval strength is higher during the second presentation of an immediate repetition than during the second presentation of a spaced repetition (Bjork & Bjork, 2006; Zhao et al., 2015). The RD effect occurs because retrieval strength is high upon presentation of the repeated target despite the prime having been poorly encoded. In effect, immediate stimulus repetition for ignored primes ‘tricks’ the memory system. The combined increase in storage strength for a repeated prime-target pair can be less than for a single, not-repeated target word encoded well. This interpretation has the added benefit of readily explaining the absence of an RD effect for attended primes (Experiment 3b; Collins et al., 2018). Although repeated targets following attended primes are subject to high retrieval strength, robust prime encoding compensates for the diminished increase in storage strength associated with target encoding.

Links to Neural Repetition Suppression

The deficient processing theory and NTD offer frameworks for understanding the RD and spacing effects, but neither are explicit about the mechanisms that produce these effects. Research on repetition suppression provides insight to the neural correlates of these mechanisms. Repetition suppression is a well-established phenomenon marked by decreased neural activity for repeated stimuli. This decreased neural activity is transient in nature and correlates strongly with spacing effects and repetition priming (Vanstrien, Verkoeijen, Vandermeer, & Franken, 2007; Xue et al., 2010, 2011; Zhao et al., 2015). Specifically, the magnitude of repetition suppression has been found to be inversely proportional to the spacing between repeated stimuli and directly proportional to the amount of repetition priming (Zhao et al., 2015). These features of repetition suppression correspond well to the key characteristics of the NTD (Bjork & Bjork, 1992): Priming provides an estimate of retrieval strength, whereas repetition suppression measures decrements in storage strength improvements.

Although studies of the spacing effect indirectly implicate a mechanism that weakens encoding for immediate repetitions, to our knowledge the RD effect is the first behavioural finding that directly implicates diminished encoding for immediate repetitions relative to an item presented just once. This contrast is central to findings of repetition suppression in brain imaging studies. Together with studies that have linked repetition suppression with the spacing effect (Xue et al., 2010, 2011; Zhao et al., 2015), the results of the present study point to the possibility that repetition suppression is a neural correlate of the processes that drive the RD effect.

Prediction Errors and Event Segmentation

The theoretical accounts described above frame the RD effect in terms of impaired encoding of repeated targets relative to not-repeated targets. In contrast, a different frame for the RD effect might focus on up-regulated encoding for not-repeated targets relative to repeated targets. For example, the predictive interactive multiple memory systems (PIMMS; Henson & Gagnepain, 2010) assumes a continuous bi-directional flow of information (Henson & Gagnepain, 2010) in which top-down cognitive processes generate expectations about incoming perceptual information. Robust encoding occurs when bottom-up stimulus-driven processing conflicts with top-down cognitively driven expectations (Henson & Gagnepain, 2010). A mismatch between perception and expectation serves as a learning moment, triggering the up-regulation of encoding and improving subsequent memory. In the context of the present study, when participants see a target word that matches the previously seen prime, expectations are met and little learning occurs. When the target word is different, however, a prediction error occurs and encoding of the target word increases.

The general notion of prediction error mediating encoding is also captured in the event segmentation framework described by Zacks and colleagues (Zacks & Swallow, 2007; Zacks & Tversky, 2001; Radavansky & Zacks, 2014). In this framework, prediction error mediates memory encoding that defines the boundaries between events/episodes. When prediction error is low, well-predicted ongoing processing is integrated into the current event structure. In contrast, a high level of prediction error signals the need to create a new event structure into which ongoing processing can be integrated. Indeed, prior studies have indicated increased medial temporal lobe activity at these event boundaries (Kurby & Zacks, 2008). With reference to the present study, the transition between prime and target on not-repeated trials may constitute an event boundary, whereas the transition between prime and target on repeated trials fails to elicit a new event boundary (Collins, Rosner, & Milliken, 2018). By this view, spacing between repeated stimuli would also promote the encoding of separate event representations, and thus improve memory for spaced relative to immediate repetitions.

The Ubiquity of Deficient Processing Due to Repetition

The primary aim of the present study was to examine the relation between the RD and spacing effects in recognition memory. Indeed, the results here are consistent with the view that deficient processing for immediate repetitions underlies the RD effect, and that this same deficient processing mechanism contributes to the spacing effect. A secondary objective of the present study was to highlight that deficient processing of immediate repetitions plays an important role in a wide range of behavioural phenomena. Extending this idea a step further, the RD effect in recognition reported here parallels a number of immediate repetition effects in the attention and performance literature. Attention shifts more efficiently to targets at previously uncued than previously cued locations (the IOR effect; Posner & Cohen, 1984; for reviews see Klein, 200, Lupianez, 2010), visual search is captured by new rather than old objects (Yantis & Jonides, 1984), and identification is often impeded for targets that match immediately preceding primes (Milliken, Joordens, Merikle & Seiffert, 1998; Milliken, Lupianez, Debner & Abello, 1999; Spadaro, He & Milliken, 2012). All of these results fit with the view that deficient processing of immediate repetitions has broad consequences for performance, both within and beyond the memory domain.

Conclusion

The present study converges with prior studies of the RD effect, and illustrates a link between this effect and spacing effects in recognition memory. The results here demonstrate that the RD effect is reliable, that it is mediate by spacing, and that the processes produce this mediating effect of spacing on the RD effect may also contribute to the well-known spacing effect. We have speculated that these processes may also be captured by repetition suppression effects commonly observed in neuroimaging studies (Xue et al., 2010, 2011; Zhao et al., 2015). The RD effect may therefore constitute a direct behavioural correlate of the deficient encoding of repetitions measured by repetition suppression.

Acknowledgements

Financial support for this study was provided in part by a Natural Sciences and Engineering Research Council of Canada Discovery Grant awarded to Bruce Milliken. The funding agreement ensured the authors' independence in designing the study, interpreting the data, writing, and publishing the report. The authors report no conflicts of interest.

Appendix A

Word pool for Experiment.

CURVE, MONEY, TOWER, WHEEL, TABLE, CHAIR, DROVE, GROUP, STEEP, STERN, DAILY, TOTAL, WATCH, PILOT, WATER, SHORT, NOVEL, MONTH, SHEER, CABLE, GUIDE, CATCH, BRIDE, CLEAN, TITLE, SPRAY, SOLID, MAJOR, CLIMB, THROW, COAST, OLIVE, RIVAL, TRUTH, IDEAL, GLOVE, STAMP, JEWEL, ADULT, PURSE, GUARD, SWIFT, WORST, CHARM, UNCLE, SIGHT, FLASH, STORY, JUICE, TRADE, PITCH, SAUCE, FANCY, SHOCK, STRIP, BLIND, BROOK, START, GLARE, DRIVE**,** TOUGH, CLERK, PEACH, PHONE, KNOCK, OFFER, GLEAM, WOUND, SPEED, PUPIL, LIGHT, VALUE, EVENT, CREEK, RANCH, CRASH, TRACE, MOTOR, SHAPE, SMART, EXTRA, SHIRT, VOICE, ANGLE, STAKE, RADIO, MATCH, TODAY, BRICK, SLOPE, BREAD, SWEAR, PARTY, BREAK, CHILL, TRAIN, UPPER, WORLD, GLASS, MOVIE, PROOF, NOBLE, STRAW, SCORE, BASIS, CLASS, EMPTY, STATE, AGENT, MAGIC, FRONT, FROWN, CABIN, BIRTH, FLOOR, CIGAR, PIANO, CHOKE, SLIDE, COUNT**,** TWIST, FEVER, TRICK, DELAY, TOAST, SPOON, DREAM, CHEST, STUFF, CRAWL, LUNCH, INNER, TASTE, BENCH, NURSE, CHAIN, NERVE, RANGE, ISSUE, CLOUD, CHASE, HONEY, HORSE, PLANE, OWNER, LIMIT, PRESS, ROUND, PAINT, PRIZE, ASIDE, CANDY, TREAT, BLANK, SHAME, STOOP, MOUTH, FLAME, ANKLE, BATHE, LAUGH, MUSIC, SCALE,

POUND, OCEAN, MIGHT, CLAIM, FAINT, YIELD, CHIEF, HEART, ONION, CHEER, BRAND, PLANK, SLEEP, STUDY, TENSE, GUESS, LEAST, STOLE, SHAKE, CHILD, ROUGH, CLIFF, ORDER, REBEL, DRESS, ELBOW, WAGON, SHARP, QUOTE, TIMER, TRAIL, CROWN, STAGE, JELLY, LINEN, DRAIN, STALK, HURRY, PORCH, RIGHT, STEEL, BRUSH, TRUNK, BUNCH, PENNY, BLOCK, SERVE, STONE, SHARE, BRAIN, EARTH, SCENE, FLOUR, CHEEK, GRASS, PLANT, JUDGE, CRUMB, PRINT, SPOIL, SPOKE, SHELL, OTHER, COURT, SHEET, PAUSE, SUGAR, STICK, BLOOM, TEETH, PRIDE, WHILE, SKIRT, BLAZE, GLORY, TRACK, SPELL, CORAL, FRAME, SHORE, GRAIN, STORE, BOAST, DOUBT, SATIN, REACH, SLICE, PEARL, GRASP, PRICE, ORGAN, TRUCK, STOCK, PASTE, CRACK, COVER, SWING, WHIRL, CLOCK, RIVER, SPACE, STEAL, LEVEL, DEPTH, STILL, ROUTE, SPLIT, SCARE, FENCE, KNIFE, ACTOR, POINT, THING, FLOAT, SALAD, GRIEF, SHINE, SMELL, QUIET, SHIFT, SCENT, LEMON, ELECT, FRUIT, GUEST, MIDST, FLUSH, PIECE, OPERA, GRADE, SWEET, QUICK, NOISE, SMALL, CROSS, STAND, TROOP, VISIT, APPLE, STYLE, FIELD, BOUND, SWEAT, METAL, LEAVE, DRINK, WRIST, THUMB, MORAL, DANCE, STARE, GRANT, POISE, STOVE, GROAN, SOUND, HOUSE, SHOUT, DRIFT, SENSE, CLOTH, CROWD, LAYER, STORM, WASTE, SMILE, ROAST, SHRUG, PLATE, TRUST, PLAIN, CRUSH, COACH, HOTEL, PAPER, YOUTH, CHECK, SAINT, WRECK, SPORT, EQUAL, SMOKE, STAFF, BURST, BOARD,

LOCAL, STEAM, FORCE, ALARM, SHADE, NIGHT, WOMAN, MODEL, UNDER, WHEAT, BRIEF, TOUCH

Appendix B

		Block 1				Block 2			
		Recollection		Familiarity		Recollection		Familiarity	
Exp	Task	NR	R	NR	R	NR	R	NR	R
1	Ignore	.276	.219**	.266	.246				
2a	RSVP					.354	.366	.274	.335*
2b	Name					.321	.452***	.271	.367*
3a	Ignore	.258	.185***	.269	.198**	.206	.245**	.192	.267**
3b	Name	.220	.266***	.180	.232*	.229	.356***	.186	.289***
4a	Ignore	.241	.197*	.190	.172	.232	.246	.179	.213
4b	Ignore	.261	.244	.243	.243	.242	.286*	.214	.236

Estimates of recollection and familiarity derived from the Independence/remember-know procedure (Yonelinas, 2002; Yonelinas & Jacoby, 1995). *NR* stands for not-repeated targets, *R* stands for repeated targets. Asterisks represent contrasts of within-subject repetition effects. (* $p < .05$; ** $p < .01$; *** $p < .001$)

Appendix C

		Block 1				Block 2		
Exp	Task	NR Prime	NR Target[a]	NR Target[b]	R Target	NR Target	R Target	New
3a	Ignore	.387 (.186)	.648 (.174)	.615 (.180)	.566 (.169)	.570 (.166)	.648 (.162)	.266 (.135)
3b	Name	.517 (.183)	.509 (.147)	.520 (.166)	.578 (.144)	.522 (.135)	.674 (.143)	.192 (.110)
4a	Ignore	.373 (.156)	.581 (.165)	.572 (.179)	.548 (.143)	.564 (.160)	.600 (.167)	.258 (.142)
4b	Ignore	.372 (.163)	.605 (.188)	.579 (.200)	.585 (.188)	.570 (.176)	.605 (.189)	.226 (.148)

Complete set of mean “old” response rates to each item type at the time of test. Standard deviations are presented in parenthesis. R stands for repeated, NR stands for not-repeated.

[a] These items were paired with the not-repeated primes and were used for RD effect comparisons

[b] These items were paired with the repeated targets from block 2 and were excluded from the analysis of RD effects

CHAPTER 4 – An Instance Model of the Repetition Decrement and Spacing Effect

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Intended for submission to a special issue of the

Journal of Memory and Language

on the 1st October 2018

Preface

The previous two chapters proposed that the repetition decrement effect is driven by the deficient processing mechanism that also drives the spacing effect, and that this deficient processing mechanism is transient in nature. The current chapter presents an instance model formalising this proposal, Minerva-ALB. One key feature of the model, based on Minerva-AL, is discrepancy encoding. This feature attenuates the encoding of redundant features. The second key feature, unique to Minerva-ALB, is a temporally graded buffer that mediates the magnitude of deficient processing. Minerva-ALB predicted the entire range of repetition decrement and spacing effects observed in the prior empirical chapters. I tested the rigour of Minerva-ALB by generating a priori predictions about a novel experimental design. Specifically, the model correctly predicted a gradual decrease in the repetition decrement effect and a conventional spacing effect. The success of the model in predicting the spacing and repetition decrement effects provides convincing evidence that the two effects are, in fact, driven by the same temporally graded deficient encoding process.

Abstract

The spacing effect is the finding that repeated encoding benefits memory performance more when repetitions are spaced apart than when they are spaced close together (Bjork & Allen, 1970; Hintzman, 1974). The repetition decrement effect is a recently reported finding in which memory for immediate repetitions is worse than memory for an item presented only once in a prior study phase (Rosner et al., 2018; Collins et al., 2018). We present an instance model that demonstrates how these two effects could be related to a single underlying mechanism. The model presented here, Minerva-ALB, is a modification of Minerva-AL (Jamieson, Crump, & Hannah, 2012; see also Hintzman, 1984). Minerva-ALB modifies the discrepancy encoding process introduced in Minerva-AL such that it favours encoding of events that differ from those stored recently in a short-term memory buffer. This discrepancy encoding process diminishes the encoding of immediate repetitions but not spaced repetitions, and in so doing produces both the repetition decrement and spacing effects.

Introduction

Studying an item twice improves recognition (Greene, 1989; Hintzman, 1974, 1976) and recall (Ebbinghaus, 1885; Kynette, Kemper, Norman, & Cheung, 1990). Similarly, stimulus repetition improves performance on tests of reading speed, perceptual identification, word fragment completion, and lexical decision (Erickson & Reder, 1998; Balota & Spieler, 1999; Bodner & Masson, 1997; Meyer & Schvaneveldt, 1971).

At the same time, one of the most robust effects in the memory literature is a strong mitigating influence on the benefit of repeated encoding. Repeated encoding benefits memory performance more when repetitions are spaced apart in time than when they are spaced close together in time (Ebbinghaus, 1885), a phenomenon called the spacing effect (Bjork & Allan, 1970; Hintzman, 1974). One broad theory of the spacing effect is that repeated items undergo “deficient processing” when spaced close together. For example, repeated items spaced close together may feel familiar, which could, in turn, reduce effort in tasks that require intentional encoding. Alternatively, repeated items spaced close together may be subject to some more automatic form of habituation that diminishes encoding. Regardless of the precise cause, if the encoding of repeated items is attenuated when repetitions are spaced close together, then it ought to be possible to measure that diminished encoding for immediately repeated items relative to items presented just once – a repetition decrement effect. This repetition decrement effect was reported for the first time recently in recent work (Rosner et al., 2018; Collins, Rosner, & Milliken, 2018; Collins & Milliken, 2018; Rosner & Milliken, 2018).

The Repetition Decrement Effect

In Rosner et al. (2018), we examined the repetition decrement effect by measuring recognition of words named aloud at study. On each trial in the study phase, a briefly presented green prime word was followed by a red target word, and participants named the red target word aloud. No specific instructions were given for the green prime words. On half of the trials the green and red words were the same (repeated trials); on the other half of the trials, the green and red words were different (not-repeated trials). Following the study phase, participants completed a surprise recognition memory test. Recognition sensitivity was worse for repeated items than for not-repeated items from the study phase. To the best of our knowledge, this repetition decrement effect constitutes the first direct evidence that repetition during a study phase can impair memory in the following test phase.

In another study, Collins et al. (2018) probed the limits of the repetition decrement effect by varying the encoding task for the green prime during the study phase. There were two critical findings in their study. First, the repetition decrement effect was observed when primes were ignored (as in the study of Rosner et al., 2018) and when attention was divided during prime presentation. Second, the repetition decrement effect was absent when participants named the study phase primes and turned into a repetition benefit when participants engaged in a semantic judgment for the study phase primes (i.e., deep encoding). Together, these results suggest that the repetition decrement effect hinges on poor encoding of the primes in the prime-probe pairs presented at study.

What other conditions affect the repetition decrement effect? In all these initial studies of the repetition decrement effect, targets followed shortly after primes in the study phase. Collins and Milliken (under review) examined whether this short prime-target interval is critical to the repetition decrement effect. If so, then it follows that the processes underlying the repetition decrement effect may be shared with those underlying the well-known spacing effect in memory. Indeed, the experiment confirmed that repeated targets presented ten minutes apart in the study phase were remembered better than not-repeated targets: a reversal of the repetition decrement effect. From this perspective, the repetition decrement effect directly measures the deficient processing of repeated items that is implied only indirectly in studies of the spacing effect (Ebbinghaus, 1885; Greene, 1989; Hintzman, 1976; Russo, Parkin, Taylor, & Wilks, 1998).

In the work that follows, we present a formal model of the mechanisms that underlie the deficient processing of repetitions. We make the case using Minerva-AL, an instance-based theory of learning and memory (Jamieson, Crump & Hannah, 2012). The discrepancy encoding function of this model captures the essence of deficient processing, as it encodes in memory only features of events that are not redundant with events already encoded in memory. Building off this feature of Minerva-AL, we were able to capture a wide range of repetition decrement and spacing effects, however, to do so we needed to add two components to the model: (1) the quality of encoding for prime and target words varied; and (2) the mediating influence of discrepancy encoding on storage degraded gracefully with time.

A Brief Primer on Minerva 2

Minerva 2 (Hintzman, 1984, 1986) is an instance theory of human memory. It was initially designed to explain frequency judgments and recognition memory decisions, and has now been applied successfully to a wide range of memory phenomena (Arndt & Hirshman, 1998; Benjamin, 2010; Clark, 1997; Jamieson, Crump, et al., 2012; Jamieson, Hannah, & Crump, 2012; Jamieson & Mewhort, 2009, 2010, 2011; Kwantes, 2005; Kwantes & Mewhort, 1999; Kwantes & Neal, 2006). In the model, each stimulus encountered is encoded as a unique episodic trace. Presenting a probe triggers the retrieval of an echo that is equal to the weighted sum of all traces in memory, where each trace contributes to the echo in proportion to its similarity to the probe. The similarity of the probe to all traces in memory determines memory decisions, such as the old/new decisions required in tests of recognition.

Formally expressed, Minerva 2 is a computational theory of memory. Within the model, stimuli and their stored representations in memory are each defined by a vector consisting of *n* features. Importantly, the model does not distinguish whether the features represent stimulus-specific properties (e.g., colour) or information states within the brain (e.g., neural potentials). Both interpretations are equally valid, and unimportant to the model's predictions. Features within these vectors have one of three values, +1, -1, or 0. Positive values represent a feature that is present, while negative values represent a feature that is absent. Values of 0 can represent indeterminant, irrelevant, or unencoded features of a stimulus.

In the model, memory is represented by the two-dimensional matrix *M*. This matrix consists of rows that store individual episodes and columns that store features. An event, *E*, is encoded as a trace in memory. A model parameter *L* defines the probability of successful storage of each feature. Increasing *L* results in a more robust and complete representation of the object or experience in memory.

Probing memory with a cue activates all traces in proportion to their similarity to the probe. The similarity of probe *P* to trace *i* in memory, M_i, is computed as:

$$S_i = \frac{\sum_{j=1}^{n} P_j \times M_{ij}}{n_r}$$

where P_j is the value of *j*th feature of the probe, M_{ij} is the value of the *j*th feature of the *i*th row in memory, *n* is the number of features in the vectors under comparison, and n_R is the number of non-zero features in the vectors under comparison. Similarity is +1 when the row is identical to the probe, -1 when the row is opposite to the probe, and 0 when the row is orthogonal to the probe.

Trace *i*'s activation, A_i, is a nonlinear function of probe similarity:

$$A_i = S_i^3$$

Although a probe activates all traces in memory, the activation function sharpens the similarity value and ensures that only those traces that are most similar to the probe are activated strongly, boosting the signal-to-noise ratio. This aspect of the model serves to boost the signal-to-noise ratio and is critical to making the theory an instance theory of memory.

When a probe is presented to the model, information retrieved from memory produces an echo, represented by the vector *C*. This echo has two properties: intensity and content. These properties are used to simulate performance on memory tests such as recognition and cued recall (Hintzman, 1986), respectively. The intensity of the echo, *I*, is given by:

$$I = \sum_{i=1}^{m} A_i$$

where m is the total number of traces in memory, and A_i is the activation of trace *i* in memory. Thus, the intensity of an echo is the sum of the activation that a probe elicits in memory. The echo's content is computed separately. Each feature in the echo takes on a value that sums across all corresponding features in the $i = 1 \ldots m$ traces in memory, weighted by the activation of each trace:

$$C_j = \sum_{i=1}^{m} A_i \times M_{ij}$$

Note that in all cases, the value of the echo is normalised:

$$C_j' = \frac{C_j}{\max|C_{1,n}}$$

As it is an instance theory of memory, Minerva 2 assumes the independent encoding of items. Each studied item produces a new row in the memory matrix, with no concern for order or repetition. This independent encoding of list items predicts monotonic improvement in memory with repeated exposure to stimuli (see Hintzman, 1988). This property of the model is incongruent with the repetition decrement effect (Collins et al., 2018; Rosner et al., 2018; Collins and Milliken, under review). As we will demonstrate, there are no values of *L* (or combination of values) for which Minerva 2 predicts better sensitivity for a word studied once than for a word studied twice or more times. To predict the repetition decrement effect, a modification of the model is necessary.

Minerva-AL, Discrepancy Encoding, and the New Theory of Disuse

The Minerva-AL model (AL for *associative learning*) is a modification of Minerva 2 developed by Jamieson, Crump et al. (2012) that served as the focus of our modelling of the repetition decrement effect. The critical difference between Minerva-AL and its predecessor is the introduction of a learning component. Like Minerva 2, an initial event vector, *E*, is simply stored as a row in the memory matrix, *M*. Upon experiencing a new probe event, however, the probe event is not added to the memory matrix. Instead, only information in the probe that the probe does not retrieve from memory is encoded to the memory matrix. Computationally, a probe event generates an echo, *C*, from memory. The probe event is compared to the echo, and the representation of the probe added to memory consists of the arithmetic difference between the two vectors. Jamieson, Crump et al. (2012) called this learning mechanism *discrepancy encoding.* Importantly, discrepancy encoding implies that the retrievability of an event affects the future learning of that event, with learning being more robust when retrievability is poor.

Discrepancy encoding is represented in the model by simple subtraction. Assume M_{ij} is the *j*th feature of the *i*th trace in memory, E_j is the *j*th feature of the event vector, and C'_j is the *j*th feature of the normalised echo, then:

$$M_{ij} = E_j - C'_j$$

with probability L ($M_{ij} = 0$ with probability $1 - L$).

To implement discrepancy encoding, the similarity calculation in Minerva-AL differs from Minerva-2. Discrepancy encoding results in a vector that represents the difference between two representations, each with feature values ranging from -1 to +1. Therefore, the vector resulting from discrepancy encoding may include values ranging from -2 to +2. The similarity calculation had to be altered to account for this new range of values. This change led to the replacement of the similarity formula in Minerva 2 with a standard vector cosine (Jamieson, Crump, et al., 2012; Kwantes, 2005):

$$S_i = \frac{\sum_{j=1}^{n} P_j \times M_{ij}}{\sqrt{\sum_{j=1}^{n} P_j^2}\sqrt{\sum_{j=1}^{n} M_{ij}^2}}$$

where P_j is the value of the *j*th feature in the probe, M_{ij} is the value of the *j*th feature of the *i*th row in memory, and *n* is the number of features in the cue-fields of the vectors under comparison. This measure is conceptually identical to the similarity measure in Minerva 2 but is mathematically compatible with the increased range of possible echo values.

An important consequence of discrepancy encoding is that the opportunity for robust learning is greatest during the initial presentation of a stimulus – learning during subsequent presentations of the same stimulus is degraded to the extent that earlier representations can be retrieved from memory. This discrepancy encoding feature of Minerva-AL allows it to account for a wide range of animal learning phenomena (Jamieson, Crump et al., 2012). Here, the discrepancy encoding mechanism held promise in modelling the repetition decrement effect (Collins et al., 2018; Rosner et al., 2018), and ultimately the link between the repetition decrement and spacing effects (Collins & Milliken, under review; Hintzman, 1976; Rosner et al., 2018).

Although not a computational theory, the new theory of disuse (Bjork & Bjork, 1992, 2006) bears a resemblance to Minerva-AL. The new theory of disuse describes memory as possessing two strengths: A storage strength and a retrieval strength. The degree to which an item is learned and represented in memory is its storage strength, while the accessibility of that representation is its retrieval strength. Whereas storage strength is unaffected by the time that has passed since an item was encoded, retrieval strength decreases with time that has passed since encoding. Importantly, these two strengths interact; retrieval strength mediates increases in storage strength. When retrieval strength is high, there is little need for learning, and increases in storage strength are minimal. Conversely, when retrieval strength is low, there is much need for learning, and increases in storage strength are significant. Thus, transient increases in retrieval strength, such as when an item is in an ‘episodic buffer’ (Cowan, Saults, & Blume, 2014), may impair the encoding of immediately repeated items. In contrast, a low level of retrieval strength, such as occurs when time has passed since an item was initially encoded, will produce a robust increment in storage strength. The new theory of disuse has received increasing support from brain imaging research on repetition priming and repetition suppression (Xue et al., 2010, 2011; Zhao et al., 2015).

Many of the assumptions of the new theory of disuse are formalised in Minerva-AL. For example, monotonic increases in storage strength with repeated study are captured in Minerva-AL by the fact that repeated encoding always improves echo intensity at test. The proposal that increases in storage strength are mediated by retrieval strength is captured in Minerva-AL by the discrepancy encoding process. There is, however, no analogue in Minerva-AL for decreases in retrieval strength with time passed since encoding. As we will show in the present study, a temporal gradient for retrieval strength is crucial for predicting the repetition decrement and spacing effects of interest here.

In the remainder of this article, we describe applications of models inspired by Minerva-AL to several recent demonstrations of the repetition decrement effect (Collins et al., 2018; Rosner et al., 2018; Collins & Milliken, under review). All of the simulations follow a similar procedure, beginning with a study phase in which prime and target words are encoded in memory. For half of the study phase trials, the prime and target words consist of the same 20 feature vector, an approximation of repeated trials from the empirical studies. For the other half of the study phase trials, the prime and target words consist of different 20 feature vectors, an approximation of not-repeated trials from the empirical studies. On any given trial, a prime is first presented and encoded into memory with learning rate L_P. This learning rate can vary to simulate the different prime encoding conditions (Collins et al., 2018; Collins and Milliken, under review). A target word is then presented to memory and subjected to the discrepancy encoding process. The resulting vector is encoded in memory with a fixed learning rate, $L_T = .5$. Following completion of this learning phase is a simulated test phase.

The test phase is mathematically identical in Minerva 2 and Minerva-AL. On each test trial, a probe is presented to memory. The probe can be either a previously studied target word or a new unseen word. In either case, the probe generates an echo intensity value based on the similarity between it and all traces in memory, M. The echo intensity is used to make ‘old’ or ‘new’ decisions about the probe. We simulate an idealised, unbiased participant by setting a neutral criterion: If the echo intensity of a given probe is greater than the median intensity for all probes, then the model assigns an ‘old’ judgement. If the echo intensity of a given probe is less than the median intensity for all probes, then the model assigns a ‘new’ judgment. When an ‘old’ judgment is made for an old target word, this is a ‘hit’. When an ‘old’ judgment is made for a new word, this is a ‘false alarm’. Throughout the study, when discussing either the empirical data or results of the model, we focus on hits and false alarms as dependent measures.

Simulations of the Formal Model

We now simulate the repetition decrement effect reported in several recent studies (Collins et al., 2018; Rosner et al., 2018; Collins and Milliken, under review). In Section 1, we simulate the original repetition decrement effect (Rosner et al., 2018). This section demonstrates that, without modification, both Minerva 2 and Minerva-AL fail to predict the repetition decrement effect. We also propose a modification of Minerva-AL that does predict the repetition decrement effect. In Section 2, we highlight a serious limitation of this modified model and propose instead a broader change to the model, which we call Minerva-ALB. According to Minerva-ALB, discrepancy encoding is guided by the contents of a buffer of items added to memory, with representations that degrade sharply with each item added. In section 3, we use the new model to predict results from the *hybrid* method reported by Collins and Milliken (under review), in which immediate and spaced repetition are contrasted. Finally, in

Section 4, we use the same model to generate a priori predictions about a new experimental design that varies the spacing of repeated words in a single list. This new design aimed to measure both the repetition decrement and spacing effects in the same experiment. We report model predictions and new empirical results with this new design.

Section 1: The Original Repetition Decrement Effect (Rosner et al., 2018)

In the original repetition decrement effect experiment (Rosner et al., 2018), a green prime word followed by a red target word was presented on each study phase trial. Participants ignored the green prime and named the red target aloud. On half of the trials, the green prime and red target were the same word, referred to as a repeated trial. On the other half of trials, the green prime and red target were different words, referred to s a not-repeated trial. Following the learning phase, participants completed a surprise recognition memory test.

We applied both Minerva 2 and Minerva-AL to a 120-trial learning phase identical in design to the empirical study, with 60 repeated trials and 60 not-repeated trials. For each trial, a prime word was encoded into memory with a relatively low learning rate, to simulate that participants were instructed to ignore the prime. Next, the target word was presented to the models and encoded with a comparatively high learning rate, to simulate the naming of the target. For the Minerva-AL simulation only, the target was subjected to the discrepancy encoding process described above before being encoded and added to memory. Following the learning phase, memory was tested for all previously encoded target words as well as an equal number of new lures. The test phase was identical for the Minerva 2 and Minerva-AL simulations. The key issue here is whether discrepancy encoding in Minerva-AL would predict better recognition for not-repeated than repeated trials.

We conducted 240 independent replications of all simulations, corresponding to ten times the number of participants used in the corresponding empirical studies (Collins et al., 2018; Rosner et al., 2018). The resulting model predictions had standard errors (SE) typically less than a third of a percentage point, and so no formal inferential statistics were conducted on the model predictions. For both models, we ran a simulation with L_P set to .15 or .30, and L_T set to .50. Table 1 presents the mean percentage of "old" decisions produced by the models, collapsed across replications, together with results from prior empirical studies of the repetition decrement effect using a comparable method (Collins et al., 2018; Rosner et al., 2018).

Table 1 Simulation of repeated/not-repeated procedure with ignored prime. SE in parenthesis.

			Mean Proportion of "Old" Judgements		
Source	Exp.	L_P / *Prime Task*	*Not-Rep.*	*Rep.*	*New*
Rosner et al. (2018)	Exp. 2	Ignore	65.9(~)	61.8(~)	21.4(~)
Collins et al. (2018)	Exp. 1	Ignore	67.8 (2.9)	62.1 (3.5)	22.4 (3.2)
		Div. Attention	50.3 (2.2)	46.5 (2.8)	22.7 (2.6)
Minerva 2		.15	65.2 (0.3)	66.2 (0.3)	34.3 (0.2)
		.30	62.2 (0.3)	69.2 (0.3)	34.3 (0.2)
Minerva-AL		.15	59.8 (0.4)	62.7 (0.3)	38.8 (0.2)
		.30	57.4 (0.4)	65.1 (0.3)	38.8 (0.2)
Minerva-AL		.15	69.6 (0.3)	49.6 (0.4)	40.4 (0.2)
(*modified*)		.30	66.0 (0.3)	54.8 (0.3)	39.6 (0.2)

As Table 1 shows, both Minerva 2 and Minerva-AL predicted improvements in recognition with repetition, with the effect being larger for the higher level of L_P. The failure of discrepancy encoding in Minerva-AL to predict the repetition decrement effect can be explained as follows. First, poorly encoded primes do not contribute strongly to the echo, and therefore very little discrepancy encoding that is specific to the prime takes place for repeated targets. Second, although increasing L_P does increase the magnitude of prime-specific discrepancy encoding, it also produces a stronger trace of the prime in memory, which improves recognition for repeated trials. Unfortunately, the balance of the two forces falls in favour of the twice-encoded event, and so the theory produces a repetition benefit rather than a cost. We concluded that a modified discrepancy encoding process is necessary to predict the repetition decrement effect.

We then modified Minerva-AL by applying discrepancy encoding in a substantially different way. Specifically, rather than subtracting an echo C from the target word before encoding, our modified Minerva-AL model subtracts the vector of the immediately preceding prime word from the repeated target word before encoding the resulting vector in memory. Note that the discrepancy encoding process of this modified model is meaningfully different from that in Minerva-AL – discrepancy encoding is driven by a representation of the item immediately prior to the target, rather than by the echo from all items in memory. Our simulation with the modified model addressed whether this change allows it to predict the repetition decrement effect where Minerva-AL failed to do so.

For the modified Minerva-AL, an additional parameter was necessary: L_{Disc} weights the degree of interference that occurs due to discrepancy encoding. Setting L_{Disc} to .00 produces mathematically identical predictions to Minerva-2, as no discrepancy encoding takes place. Conversely, setting L_{Disc} to 1.00 eliminates all overlapping features between the prime word and target word before encoding. Throughout the study, we set L_{Disc} at .80 unless otherwise noted. The predictions of this model are presented in the bottom two rows of Table 1.

In contrast to both Minerva 2 and Minerva-AL, the modified Minerva-AL predicted poorer recognition for repeated than not-repeated targets for both levels of L_P. These results align qualitatively with the empirical results presented in the top three rows in Table 1 (Collins et al., 2018; Rosner et al., 2018; Collins et al., 2018), and differ qualitatively from the predictions of Minerva 2 and Minerva-AL.

Why is it that only the modified Minerva-AL predicts the repetition decrement effect? At the beginning of the study phase, the memory matrix M is empty. When presented with the prime, the learning rate L_P is applied, resulting in an impoverished vector being stored in memory. In the modified Minerva-AL only, the prime-specific discrepancy encoding process is applied to the target representation. When the prime and target words differ, little to no discrepancy encoding occurs. When the prime and target words are the same, however, the discrepancy encoding process removes redundant features that overlap between the prime and target vector. Consequently, following discrepancy encoding and application of the learning rate, L_T, the resulting vector copied into memory is a more robust representation for not-repeated targets than repeated targets. As the prime-specific discrepancy encoding process is responsible for this difference in robustness of the target representation, only the modified Minerva-AL model predicts the repetition decrement effect.

Although the modified Minerva-AL model predicted a larger repetition decrement effect and higher false alarm rates than observed in the empirical studies (Collins et al., 2018; Rosner et al., 2018), these differences can be eliminated with minor changes to the model. Increasing L_P would arbitrarily improve memory for repeated targets and shrink the repetition decrement effect, as we will demonstrate below. Furthermore, increasing L_T would arbitrarily increase both repeated and not-repeated hit rates, without altering the direction of the repetition effect. Finally, introducing a multiplicative coefficient to the model's decision criterion would affect hits and false alarms by shifting bias. A more conservative bias would lower both hit and false alarm rates, and vice versa. Together, changes to these parameters could easily have been implemented to produce close fits between the model and empirical data. However, our aim was not to overfit the model. On the contrary, the critical result is that the modified Minerva-AL model effectively predicts a qualitative pattern of interest, the repetition decrement effect (Collins et al., 2018; Rosner et al., 2018).

Section 2: The Lag Procedure (Rosner et al., 2018)

In Experiment 3 of Rosner et al. (2018) two green primes and a red target presented on each trial. On not-repeated trials, all three words were unique. On repeated trials, one of the green prime words was later repeated as the target word. This lag manipulation was implemented between groups. For the Lag-0 group, the second prime was the same as the target. For the Lag-1 group, the first prime was the same as the target. The results are displayed in the top two rows of Table 2 – a repetition decrement effect was observed for both lag conditions.

This pattern of results presents a problem for the modified Minerva-AL, as the discrepancy encoding process in this model gives a privileged role to the item that immediately precedes the target. A simulation of the lag procedure confirmed that the modified Minerva-AL predicts a repetition decrement for the Lag-0 condition but not for the Lag-1 condition (see Table 2). What appears necessary is a discrepancy encoding process that emphasises representations of items presented close in time to the target without assigning a privileged role to the one item that immediately precedes the target.

Table 2 Simulation of lag manipulation. SE in parenthesis.

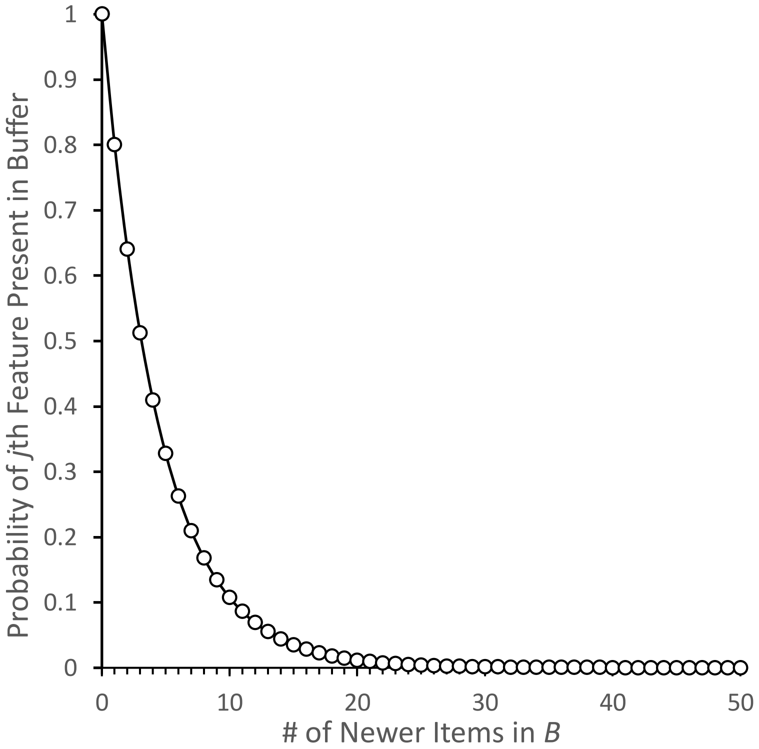
Source		Lag	% 'Old' Judgments		
			Not-Rep. Target	*Rep. Target*	*New*
Rosner et al. (2018)	Exp. 3	0	54.7(~)	48.5(~)	18(~)
		1	58.8(~)	54.4(~)	23(~)
Minerva-AL (*modified*)		0	66.7 (0.3)	49.8 (0.4)	41.7 (0.2)
		1	61.0 (0.3)	63.9 (0.4)	37.5 (0.2)
Minerva-ALB		0	60.6 (0.4)	54.4 (0.4)	42.5 (0.2)
		1	60.3 (0.4)	56.3 (0.4)	41.7 (0.2)

To address this issue, we added a continuous buffer, *B*, to Minerva-AL. We call this new model Minerva-ALB. Like the original Minerva-AL, Minerva-ALB implements discrepancy encoding by subtracting an echo, *C*, from each event, *E*, before copying the resulting vector into memory. Unlike Minerva-AL, however, the contents of the echo are determined by the buffer, *B*, rather than memory, *M*. The critical property of the buffer is that it encodes representations with a temporal gradient, such that items presented most recently have the most robust representations, and items presented successively further back in time have less robust representations. This temporal gradient is created by applying L_{Disc} to all items in the buffer each time an item is added to the buffer. Application of L_{Disc} to items in the buffer probabilistically assigns the value of zero to features of traces in the buffer. Successive application of L_{Disc} to the same item representation degrades the item representation continuously until all its features have the value of zero, effectively nullifying that representation. Now, consider how this application of L_{Disc} to items presented successively across time and appended to the buffer impacts the representational content of the buffer. When an item *a* is appended to the buffer, L_{Disc} is applied to that item for the first time. When a following item *b* is appended to the buffer, L_{Disc} is applied to item *a* for the second time, and to item *b* for the first time, and so on. In this manner, the buffer comes to store robust representations of items that have occurred most recently and progressively less robust representations that have occurred less recently. Therefore, when an echo based on the content of the buffer is generated, the content of the echo is weighted in accord with a temporal gradient, with the most recent items weighted most heavily. Practically speaking, this property of the buffer implies that an item's contribution to discrepancy encoding decreases exponentially with intervening study events. Mathematically, the feature decay of events in the buffer can be modelled as:

$$B_i = W_i \times L_{Disc}^{n}$$

where *n* is the number of items stored in the buffer since W_i. The plot of *j*th feature decay of items in the buffer can be seen in Figure 1.

Figure 1. Decay of *j*th feature of *i*th trace in buffer *B* as a function of additional items entering the buffer when L_{Disc} = 0.80.



This modification avoids the arbitrary assumption of the modified Minerva-AL that discrepancy encoding should apply only to immediately repeated targets. Minerva-ALB applies discrepancy encoding to all words entering memory and does not privilege immediately repeated information. Information in the buffer degrades gradually with time and intervening study in line with the Ebbinghaus forgetting curve (Ebbinghaus, 1885; Murre & Dros, 2015). The proposed buffer was purposefully designed to capture the construct of retrieval strength as described in the new theory of disuse (NTD; Bjork & Bjork, 1992), and is conceptually similar with other proposals that memory involves a buffer (Baddeley, 2000; Miller, Galanter, & Přibram, 1976)

For simplicity and efficiency of simulation, we ignored the potential effects of the buffer at test. The 10-minute math distractor task separating study and test phases would have rendered any effect of the buffer at test negligible. Using this new model, Minerva-ALB, we then repeated the simulation of the Lag-0 and Lag-1 conditions of Rosner et al. (2018). The results are presented in the bottom two rows of Table 2.

Minerva-ALB accurately predicts the pattern of data observed in the lag procedure; that is, better memory for not-repeated than repeated targets for both the Lag-0 and Lag-1 conditions (Rosner et al., 2018). Whereas increasing lag in the modified Minerva-AL eliminates the repetition decrement effect, increasing lag in Minerva-ALB mediates the repetition decrement effect but does not necessarily eliminate it. Changes in the repetition decrement effect as a function of lag between prime and target owe to changes in discrepancy encoding that occur as a function of the content of the buffer. With each item added to the buffer between prime and target presentation, the robustness of the prime representation in the buffer degrades, which in turn lowers its contribution to discrepancy encoding, and reduces the repetition decrement effect. We explore this temporal spacing effect further in the remaining sections of the study.

Section 3: The Hybrid Immediate/Spaced Repetition Procedure (Collins et al., under review)

We now apply Minerva-ALB to the *hybrid* procedure developed by Collins and Milliken (under review). The goal of the hybrid procedure was to compare the effects of immediate and spaced repetition with a stronger spacing manipulation. To address this issue, a second study block was added after the first. The first study block was identical to that used in prior studies. Participants named aloud a red target that followed the presentation of a green prime. There were 80 not-repeated trials and 40 repeated trials. The second study block consisted of words previously seen as primes in the first study block (40 items) and words not previously seen in the experiment (40 items). In Experiment 3a of the study by Collins and Milliken, participants ignored the green primes, whereas in Experiment 3b participants named aloud the green primes. Participants in both experiments named aloud all items in the second study block. The first study block allowed us to measure immediate repetition effects on later recognition memory. The second study block allowed us to measure spaced repetition effects on later recognition memory. The temporal interval between primes in the first study block that later repeated in the second study block was about 10 minutes, but varied both across items and across participants as a function of item order and different times required by participants to read the study instructions for the second study block.

Following the second study block there was a 10-minute math distractor task and then a recognition memory test. One-third of the words on the recognition test were new lures, and two-thirds of the words were the previously studied old words. Table 3 summarises the results. The most important finding was an interaction between repetition and spacing in both experiments. In

Experiment 3a, where participants ignored primes in the first study block, a repetition decrement effect was observed for immediate repetitions whereas a repetition benefit was observed for spaced repetitions. In Experiment 3b, where participants named primes in the first study block, a repetition benefit was observed for both immediate and spaced repetitions, but it was larger for spaced than immediate repetitions. The next step was to examine whether Minerva-ALB predicts this robust interaction.

Table 3. Summary of hit-rates from Collins and Milliken (under review). SE in parenthesis.

		Item Type				
		Immediate		Spaced		
Exp.	Prime Task	Not-Rep Target	Rep Target	Not-Rep Target	Rep Target	New Lure
3a	Ignore	64.8	56.6	57.0	64.8	26.6
		(2.9)	(1.7)	(2.8)	(2.7)	(2.3)
3b	Name	50.9	57.8	52.2	67.4	19.2
		(2.4)	(2.3)	(2.3)	(2.4)	(1.8)

Applying Minerva-ALB to the hybrid procedure was straightforward. The first study block was simulated as described in earlier sections, with the number and proportion of not-repeated and repeated targets adjusted accordingly. The second study block was then simulated in the same manner, with both new targets and repeated targets from the previous block. The recognition test was simulated as in earlier sections, with the proportions of old items and lures adjusted in accord with the constraints of the hybrid procedure. Simulated results from the model were generated for 360 replications at each L_P, corresponding to ten times the number of participants tested by Collins and Milliken (under review). L_P

varied in .05 increments from .00 to 1.00. The results, collapsed across the replications, are presented in Figure 2.

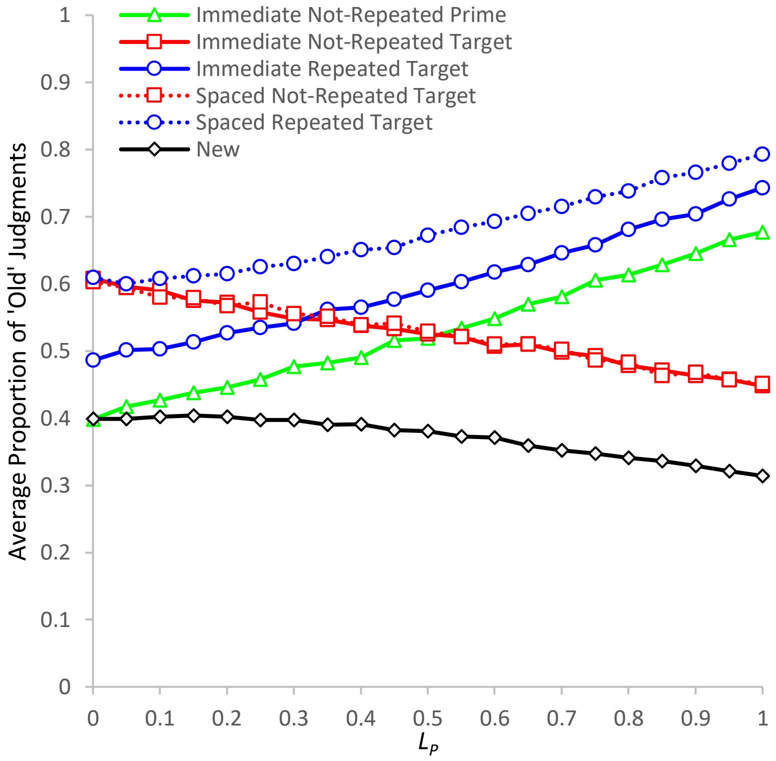


Figure 2. Mean proportion 'old' predictions for 360 replications of the hybrid procedure as a function of L_P.

Minerva-ALB predicted the key interaction nicely, as well as other properties of the empirical data. For low values of L_P, immediate repetition hurt recognition whereas spaced repetition produced a trend toward a repetition benefit. For higher values of L_P, a similar interaction was observed, although in this case it was expressed in a smaller repetition benefit for immediate repetition than spaced repetition. The consistency of this interaction across levels of L_P is captured by the near equivalent performance for immediate and spaced not-repeated items on the one hand and the consistently superior performance for spaced repeated than immediately repeated items on the other hand. Clearly, Minerva-ALB captures the well-known spacing effect, according to which repeated encoding benefits memory more for spaced than immediate repetitions (Bjork & Allen, 1970; Cuddy & Jacoby, 1982).

Mathematically, the model makes this prediction because of the influence of the buffer on discrepancy encoding. As items are appended to the buffer, the representation of items already in the buffer is degraded. Thus, whereas an immediate repetition may result in significant discrepancy encoding for the target due to a fresh representation of the prime in the buffer, the influence of that same prime on future discrepancy encoding decreases with each item added to the buffer. For repetitions with dozens of intervening items or more, the representation of the prime is often wholly degraded, and the encoding of the target is unaffected by discrepancy encoding. The result is a consistent benefit of spaced repetition across all values of L_P. Importantly, the model predicts the interaction between repetition and spacing as a natural consequence of the nature of the buffer, and not because of an arbitrary decision to apply discrepancy encoding to targets in the first study block but not the second study block.

Section 4: Variable Lag

The empirical results generated by the hybrid method (Collins & Milliken, under review) and the associated model predictions suggest that the repetition decrement effect depends on the spacing between prime and target. More broadly, the results suggest that a similar mechanism drives the repetition decrement effect and the well-studied spacing effect (Bjork & Allen, 1970; Cuddy

& Jacoby, 1982). However, a shortcoming of the results of the hybrid method is that they do not demonstrate a spacing effect in the conventional sense. The spacing effect is characterised by improved memory for spaced repetitions relative to immediate repetitions, and in the case of the hybrid procedure this comparison is confounded by retention interval – relative to the recognition test, spaced repetitions occur with a shorter retention interval than immediate repetitions. Consequently, any improvement in recognition for spaced relative to immediate repetitions in the hybrid procedure could relate to retention interval differences rather than differences in encoding. In contrast, Minerva-ALB makes a clear prediction that discrepancy encoding should produce a 'true' spacing effect.

Another issue that could not be studied with the hybrid method is the continuous nature of the spacing effect. With the hybrid method, repetition effects were studied with just two spacing conditions; immediate repetition and spaced repetition of approximately 10 minutes. As representations in the buffer of Minerva-ALB degrade progressively with the addition of each new item, a more robust test of the model would take a more granular look at the spacing by repetition interaction. Specifically, Minerva-ALB predicts a repetition decrement effect with immediate repetitions that, with increasing lag, gradually shifts to a repetition benefit.

To that end, we designed a single block experiment in which the spacing of prime-target word pairs varied. Repetition of primes as targets could occur immediately or after up to three intervening prime-target pairs. This design allows much stronger conclusions regarding the link between the repetition decrement (Collins et al., 2018; Rosner et al., 2018) and spacing effects (Collins & Milliken, under review; Ebbinghaus, 1885). Of course, in addition to collecting these empirical data, we compared the results to the predictions of Minerva-ALB.

Participants. Eighteen participants completed the experiment (15 females; mean age = 19 years). Participants were recruited from the McMaster University student pool and completed the experiment for course credit or a payment of $10 CAD. All participants had normal or corrected-to-normal vision and spoke fluent English.

Apparatus and stimuli. The experimental program was run on a Mac Mini using PsychoPy open source experimental software (v1.81.0, Peirce, 2007, 2009). The stimuli were displayed on a 24-inch BENQ LED monitor. Naming responses for the study phase were detected by a Logitech Microphone Headset. Participant responses during the test phase were recorded using the keyboard. All participants were tested individually, sitting approximately 50 cm from the monitor.

During the study phase, a green prime appeared centrally followed by a red target. During the test phase, a single red word appeared centrally. Participants' response options in the test phase, "OLD" and "NEW", were displayed in white in the bottom left and bottom right corners of the screen, respectively[1]. In both the study and test phases, the background was black. Each word subtended approximately 0.8° of visual angle vertically and 5.9° horizontally. 360 five-letter high-frequency nouns (Thorndike & Lorge, 1944) were used in this experiment. The exact word lists can be found in Appendix A.

Procedure. The procedure was identical to the original repetition decrement effect study (Rosner et al., 2018). Participants ignored a green prime followed by a red target to be named aloud. On each trial, a fixation cross (1000 *ms*) was followed by a green prime word (500 *ms*), a blank screen (250 *ms*), a red target word to be named aloud (1000 *ms*), and then a final blank screen (1000 *ms*). The next trial began immediately afterwards. Following the study phase, participants completed a 10-minute math distractor task before completing a surprise recognition memory task. On each trial of the test phase, either a previously studied red target or a previously unseen lure was presented centrally, and participants were asked to respond 'old' or 'new' via a keypress. After each response, the next trial began, until all test words were exhausted.

Design. The design was similar to Rosner et al. (2018) with some exceptions. In addition to not-repeated and immediately repeated targets defined within a prime-target trial pair (hereafter referred to as the 'Lag-0' condition),

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[1] For "old" responses, participants were also required to make a remember/know classification, once again via keyboard press. The test phase instructions defined the difference between "remembering" and "knowing" in accord with the definitions provided by Rajaram (1993). These "remember" and "know" judgments were labelled "Type A" and "Type B", and mapped to the "A" and "L" keys, respectively. Remember/know data were collected for exploratory purposes but not analysed here.

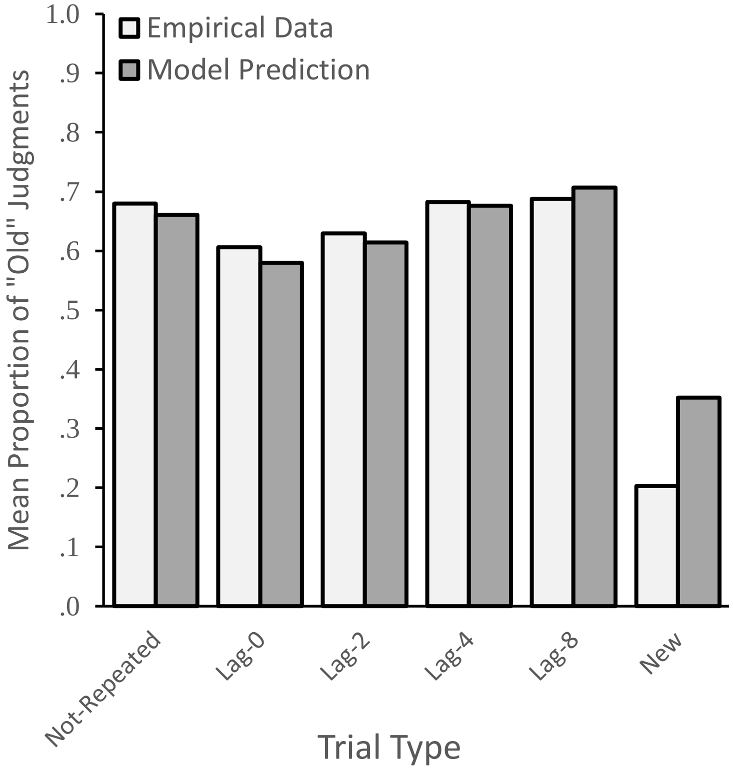
repetition of the prime as a target could now occur: (i) on the following prime-target trial (referred to as Lag-2, as there were two words between the critical prime and repeated target); (ii) after one intervening prime-target trial (referred to as Lag-4, as there were four words between the critical prime and repeated target); or (iii) after three intervening prime-target trials (referred to as Lag-8, as there were eight words between the critical prime and repeated target). Thus, the study phase included 160 trials consisting of 20 of each of the following eight trial types: Not Repeated, Lag-0, Lag-2 prime, Lag-2 target, Lag-4 prime, Lag-4 target, Lag-8 prime, Lag-8 target. These trials were pseudo-randomly intermixed to ensure that the spacing requirements of various trial types were upheld. For instance, the trial sequence {Lag-4 prime, Not-Repeated, Lag-4 target} was valid because there is a single trial between the Lag-4 prime and Lag-4 target. By contrast, the trial sequence {Lag-8 prime, Lag-2 prime, Lag-2 target, Lag-8 target} was invalid as there are only two intervening trials between the Lag-8 prime and Lag-8 target. A final consideration is that repeated trial types could intermix with themselves, such that a sequence {Lag-4 prime[a], Lag-4 prime[b], Lag-4 target[a], Lag-4 target[b]} was also valid.

The pseudo-random trial order was used for both the Minerva-ALB model predictions and the actual experiment. During the test phase, these 120 old words were randomly intermixed with 120 new words. To accommodate the trial requirements of the study and test phase, the word pool from earlier studies was randomly reassigned to 18 lists of 20 words. A latin-square counterbalancing method was used to ensure each list appeared an equal number of times in each study and test phase role, creating a total of 18 permutations of possible list orders. Participants were assigned to one of these 18 permutations based on their order of arrival.

Results

The dependent variable of interest for both the model predictions and the empirical data was the proportion of "old" responses to old (Hits) and new (False Alarms) items in the recognition test. The predictions of Minerva-ALB and the empirical results are displayed in Figure 3.

Figure 3. Mean proportion 'old' for both the empirical data and the model predictions.



Model predictions. Using a set of parameters (L_P= 0.2, L_T= 0.6, L_{Disc} = 0.85) chosen to best fit the results from Experiment 3a of the study by Collins and

Milliken (under review), we conducted 360 independent replications of the model simulations. The model predicts a repetition decrement effect in both Lag-0 and Lag-2 conditions and a positive repetition effect in both Lag-4 and Lag-8 conditions. Importantly, the model also predicts a spacing effect, with proportion old increasing monotonically from the Lag-0 to the Lag-8 condition.

Empirical results. We conducted three analyses of the empirical data. The first was a paired sampled *t*-test comparing the overall hit-rate to the false alarm rate to confirm participants' ability to recognise old words with better than chance accuracy. Second, we conducted planned paired sample *t*-tests comparing recognition for not-repeated and repeated targets at each of the four lag intervals. The purpose of these analyses was to examine the repetition effect for each of the four lag conditions. Finally, we conducted a within-subject analysis of variance (ANOVA) that included only the four lag conditions to examine whether a spacing effect occurred.

The overall hit and false alarm rates differed significantly, $t(17) = 18.96$, $p < .001$, $d = 3.83$, with more hits ($M = .657$, $SD = .165$) than false alarms ($M = .203$, $SD = .129$). This result indicates simply that participants recognized items with better than chance accuracy. The planned comparisons between the not-repeated condition and each of the lag conditions revealed a significant repetition decrement effect for the Lag-0 condition ($M = .679$, $SD = .196$ vs $M = .606$, $SD = .168$), $t(17) = 2.34$, $p = .032$, $d = 0.41$. There was a trend toward a repetition decrement effect in the Lag-2 condition ($M = .630$, $SD = .195$), but this effect was not-significant, $p = .17$. Neither the Lag-4 condition ($M = .682$, $SD = .183$) nor the Lag-8 condition ($M = .688$, $SD = .190$) differed from the not-repeated condition, *p's* > .05, but the numerical trend for these two lag conditions was opposite that for the Lag-0 and Lag-2 conditions.

Finally, the one-way ANOVA of the four lag conditions revealed a significant effect of lag, $F(3,17) = 3.10$, $p = .035$, $\eta_p^2 = .154$. As is clear in Figure 3, recognition improved for repeated words with increasing delay. A final post-hoc *t*-test that compared the Lag-0 and Lag-8 conditions was also significant, $t(17) = 2.28$, $p = .036$, $d = 0.46$, indicating superior recognition for the Lag-8 condition than for the Lag-0 condition.

Discussion. The present design with variable spacing provides a direct test of both the mediating effect of spacing on the repetition decrement effect and the spacing effect itself. Minerva-ALB predicts that immediate repetition should produce a repetition decrement effect, that increased spacing between repetitions should eliminate and eventually reverse the repetition decrement effect, and that a conventional spacing effect ought to occur. The empirical data confirmed these predictions. An ignored prime impaired recognition for immediate repetitions, and the spacing between repetitions mediated this effect. The Lag-0 condition produced a significant repetition decrement effect, the Lag-2 condition trended in the same direction, and the Lag-4 and Lag-8 conditions produced no such effect. The results of the hybrid procedure (Section 3) imply that greater spacing between repetitions than measured here does indeed reverse the repetition decrement effect. Most important, the present procedure allowed us to measure a conventional spacing effect free of confounding with retention interval between immediate and spaced repetition conditions. The analysis of the four lag conditions revealed a significant spacing effect, with recognition sensitivity increasing monotonically with increasing lag between repetitions. The empirical data and model predictions offer converging support for the view that diminished encoding of repetitions produced by a discrepancy encoding mechanism like that in Minerva-ALB underlies both the repetition decrement and spacing effects.

General Discussion

In several recent studies, immediate repetition of an item in a study phase resulted in lower recognition sensitivity in the following test phase relative to an item seen only once in the study phase – a repetition decrement effect in recognition memory (Collins & Milliken, under review; Collins et al., 2018; Rosner et al., 2018). In this study, we examined whether an instance model of memory, derived from Minerva 2 (Hintzman, 1986), can predict this set of findings. A particular focus of the modelling work was a learning component in Minerva-AL known as discrepancy encoding (Jamieson, Crump et al., 2012).

In Section 1, we demonstrated that neither Minerva 2 nor Minerva-AL predict the original repetition decrement effect (Rosner et al., 2018). However, a modification to Minerva-AL that focused discrepancy encoding exclusively on the immediately preceding prime did predict the repetition decrement effect. In section 2, an additional modification of Minerva-AL was needed to predict the lag-1 repetition decrement effect (Rosner et al., 2018); a discrepancy encoding process that depends on the contents of a temporally graded buffer. We call this modified model Minerva-ALB. In section 3, Minerva-ALB successfully predicted results from a hybrid procedure (Collins et al., under review) that measured both immediate and spaced repetition effects. In section 4, Minerva-ALB successfully predicted the results of a new experiment that varied lag systematically between prime and target within a single block of trials. Together, the results demonstrate that a discrepancy encoding process like that modelled in Minerva-ALB offers a good fit to both the repetition decrement and spacing effects.

The Repetition Decrement Effect, the Spacing Effect, and the New Theory of Disuse (Bjork & Bjork, 1992)

The present study offers converging evidence for the idea that the repetition decrement effect directly measures a process that underlies the spacing effect. The deficient processing theory attributes the spacing effect to an automatic reduction in encoding associated with repeated items (Greene, 1989; Hintzman, 1976; Russo, Parkin, Taylor, & Wilks, 1998). A particularly strong variant of deficient processing theory rests on the assumption that repeated items are encoded by retrieving the memory representation of an identical prior item, rather than re-encoding the second event anew (Cuddy & Jacoby, 1982). In effect, for short temporal intervals between repeated items, participants encode the repeated items by ‘remembering the solution rather than solving the problem’ (Jacoby, 1978).

The idea that a current event cues the retrieval of similar prior events, which in turn obviates the need to re-encode redundant aspects of the current event, is broadly consistent with the discrepancy encoding process in Minerva-AL. However, the simulations presented in Section 1 made clear that Minerva-AL predicts equally efficient memory for not-repeated and repeated items; it does not predict the repetition decrement effect. These modelling results therefore make the point that deficient processing theories of the spacing effect do not necessarily predict a repetition decrement effect. Encoding of a repeated item may well be reduced in strength due to the feature overlap with an identical item that has already been encoded. However, subsequent recognition of that item is likely to draw on the encoding of both instances of the repeated item. In this way, any ‘deficient encoding’ that occurs for the second instance of the repeated item may be compensated by the memory representation of the first instance of that repeated item. Clearly, the repetition decrement effect is not fully explained by positing simply that features of current events that are well predicted by past events are not learned (Rescorla-Wagner, 1972).

Bjork’s new theory of disuse (Bjork & Bjork, 2006; Bjork & Bjork, 1992) is an alternative theoretical framework that guided the present research. The core feature of this theory is a distinction between storage strength and retrieval strength. Whereas storage strength reflects the degree to which an item is learned and represented in memory, retrieval strength reflects the accessibility of this representation. Three key elements of the theory are: (i) storage strength improves with repeated study; (ii) retrieval strength decreases with increasing retention interval; and (iii) improvements in storage strength are mediated by retrieval strength.

Two of the key elements of the new theory of disuse are shared by multiple versions of the Minerva model. The first element of the new theory of disuse, storage strength improves with repeated study, is represented in every version of the Minerva model presented here. Each encounter with a studied item generates the creation of an additional event in memory, improving the robustness of its featural representations[2]. The third element of the new theory of disuse, improvements in storage strength are mediated by retrieval strength, is represented by the discrepancy encoding functions of both Minerva-AL and Minerva-ALB. Both models attenuate the encoding of overlapping features in repeated items.

Only one of the models, Minerva-ALB, has a formalised analogue for the new theory of disuse's second key element: retrieval strength decreases with time. In Minerva-ALB, the decrease in retrieval strength is implemented by repeated

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[2] Given that Minerva-ALB successfully predicts the repetition decrement effect, it may seem that Minerva-ALB violates the principle of monotonic improvement in storage strength. It is important to stress that repetition decrement effects for repeated targets are measured relative to a single, robust encoding event. Naming an item that was previously ignored nonetheless improves memory compared to an item that is ignored but not subsequently named. Thus, Minerva-ALB does not violate the principle of monotonic storage strength improvement.

application of L_{disc} to items in the buffer, B. Consequently, the representation of a given item in the buffer degrades with each new item added to the buffer. This gradient affects the contribution of each item in the buffer to discrepancy encoding, decreasing with each item added to the buffer. In this way, Minerva-ALB predicts that the contribution of stimulus repetition to discrepancy encoding will degrade as the interval between repetitions increases. Critically, this process enables Minerva-ALB to predict both the repetition decrement and spacing effects where Minerva-AL fails to do so.

In summary, Minerva-ALB formalises the assumptions of the new theory of disuse (Bjork & Bjork, 2006; Bjork & Bjork, 1992) within an instance-based computational model. This formalisation accounts for a variety of recent results centred on the repetition decrement effect that other variants of Minerva 2 fail to predict. In doing so, however, Minerva-ALB incorporates features that are somewhat distant from the central features of its parent model, Minerva 2. In particular, Minerva 2 (Hintzman, 1984) predicts memory phenomena by modelling retrieval from a single store of memory instances. Aside from the parameter L, Minerva 2 mostly eschews processing at the time of study. Jamieson, Crump et al. (2012) introduced a learning component to Minerva 2 called discrepancy encoding. The resulting model, Minerva-AL, held promise in predicting the repetition decrement effect because it emphasized encoding of features not represented in the echo retrieved from memory. However, Minerva-AL failed to predict the repetition decrement effect without additional modification. In Minerva-ALB, discrepancy encoding is based on the contents of a buffer that degrades rapidly with each item added to the buffer. This addition of a short-term buffer perhaps contrasts with the spirit of Minerva 2, which remains neutral about the distinction between primary and secondary memory. For this reason, it will be important for future studies to consider whether the work done by the buffer in Minerva-ALB could be modelled in other ways, such as adding temporal context to representations (Howard & Kahana, 2002) rather than adding a particular form of short-term buffer to the model.

Conclusion

Deficient encoding of repeated items has long been proposed to explain the classic spacing effect (Ebbinghaus, 1885). We propose that the repetition decrement effect is a direct measure of this deficient encoding process. Building on the idea that increments in storage strength are inversely related to retrieval strength (Bjork & Bjork, 1992, 2006), we added a temporally graded buffer to Minerva-AL. With discrepancy encoding based on the content of this buffer, Minerva-ALB successfully predicted the repetition decrement effect, the spacing effect, and the relation between them.

Appendix A

Word pool for Experiment.

CURVE, MONEY, TOWER, WHEEL, TABLE, CHAIR, DROVE, GROUP, STEEP, STERN, DAILY, TOTAL, WATCH, PILOT, WATER, SHORT, NOVEL, MONTH, SHEER, CABLE, GUIDE, CATCH, BRIDE, CLEAN, TITLE, SPRAY, SOLID, MAJOR, CLIMB, THROW, COAST, OLIVE, RIVAL, TRUTH, IDEAL, GLOVE, STAMP, JEWEL, ADULT, PURSE, GUARD, SWIFT, WORST, CHARM, UNCLE, SIGHT, FLASH, STORY, JUICE, TRADE, PITCH, SAUCE, FANCY, SHOCK, STRIP, BLIND, BROOK, START, GLARE, DRIVE**,** TOUGH, CLERK, PEACH, PHONE, KNOCK, OFFER, GLEAM, WOUND, SPEED, PUPIL, LIGHT, VALUE, EVENT, CREEK, RANCH, CRASH, TRACE, MOTOR, SHAPE, SMART, EXTRA, SHIRT, VOICE, ANGLE, STAKE, RADIO, MATCH, TODAY, BRICK, SLOPE, BREAD, SWEAR, PARTY, BREAK, CHILL, TRAIN, UPPER, WORLD, GLASS, MOVIE, PROOF, NOBLE, STRAW, SCORE, BASIS, CLASS, EMPTY, STATE, AGENT, MAGIC, FRONT, FROWN, CABIN, BIRTH, FLOOR, CIGAR, PIANO, CHOKE, SLIDE, COUNT**,** TWIST, FEVER, TRICK, DELAY, TOAST, SPOON, DREAM, CHEST, STUFF, CRAWL, LUNCH, INNER, TASTE, BENCH, NURSE, CHAIN, NERVE, RANGE, ISSUE, CLOUD, CHASE, HONEY, HORSE, PLANE, OWNER, LIMIT, PRESS, ROUND, PAINT, PRIZE, ASIDE, CANDY, TREAT, BLANK, SHAME, STOOP, MOUTH, FLAME, ANKLE, BATHE, LAUGH, MUSIC, SCALE,

POUND, OCEAN, MIGHT, CLAIM, FAINT, YIELD, CHIEF, HEART, ONION, CHEER, BRAND, PLANK, SLEEP, STUDY, TENSE, GUESS, LEAST, STOLE, SHAKE, CHILD, ROUGH, CLIFF, ORDER, REBEL, DRESS, ELBOW, WAGON, SHARP, QUOTE, TIMER, TRAIL, CROWN, STAGE, JELLY, LINEN, DRAIN, STALK, HURRY, PORCH, RIGHT, STEEL, BRUSH, TRUNK, BUNCH, PENNY, BLOCK, SERVE, STONE, SHARE, BRAIN, EARTH, SCENE, FLOUR, CHEEK, GRASS, PLANT, JUDGE, CRUMB, PRINT, SPOIL, SPOKE, SHELL, OTHER, COURT, SHEET, PAUSE, SUGAR, STICK, BLOOM, TEETH, PRIDE, WHILE, SKIRT, BLAZE, GLORY, TRACK, SPELL, CORAL, FRAME, SHORE, GRAIN, STORE, BOAST, DOUBT, SATIN, REACH, SLICE, PEARL, GRASP, PRICE, ORGAN, TRUCK, STOCK, PASTE, CRACK, COVER, SWING, WHIRL, CLOCK, RIVER, SPACE, STEAL, LEVEL, DEPTH, STILL, ROUTE, SPLIT, SCARE, FENCE, KNIFE, ACTOR, POINT, THING, FLOAT, SALAD, GRIEF, SHINE, SMELL, QUIET, SHIFT, SCENT, LEMON, ELECT, FRUIT, GUEST, MIDST, FLUSH, PIECE, OPERA, GRADE, SWEET, QUICK, NOISE, SMALL, CROSS, STAND, TROOP, VISIT, APPLE, STYLE, FIELD, BOUND, SWEAT, METAL, LEAVE, DRINK, WRIST, THUMB, MORAL, DANCE, STARE, GRANT, POISE, STOVE, GROAN, SOUND, HOUSE, SHOUT, DRIFT, SENSE, CLOTH, CROWD, LAYER, STORM, WASTE, SMILE, ROAST, SHRUG, PLATE, TRUST, PLAIN, CRUSH, COACH, HOTEL, PAPER, YOUTH, CHECK, SAINT, WRECK, SPORT, EQUAL, SMOKE, STAFF, BURST, BOARD,

LOCAL, STEAM, FORCE, ALARM, SHADE, NIGHT, WOMAN, MODEL, UNDER, WHEAT, BRIEF, TOUCH

CHAPTER 5 – General Discussion

An efficient cognitive system ought to be equipped with mechanisms to minimise the encoding of information that is already represented in memory. In the attention and performance literature, there is plenty of empirical support for the idea that attention is inhibited from orienting to objects and events in the external world that are redundant with representations stored in memory (Francis & Milliken, 2003; Law, Pratt, & Abrams, 1995; Posner & Cohen, 1984; Tipper, 1985). For example, when participants engage in visual search, attention orients with preference to new objects rather than to old objects (Yantis & Jonides, 1984). Although there is a clear case for redundancy mediated attentional systems in the brain, the case for a similar principle in the memory literature is less clear.

Unlike in the attention literature, however, most research on memory suggests that repeated opportunities to encode items benefit subsequent remembering. Indeed, repetition enhances participants' performance on many implicit memory tests (Bodner & Masson, 1997; Graf & Mandler, 1984; Tulving et al., 198) and explicit memory tests alike (Eichenbaum, 2001; Woodward & Bjork, 1990, Kynette et al., 1990). For example, repeated maintenance rehearsal of a word improves the likelihood of recognition for that word (Glenberg, Smith, & Green, 1977). These findings point to a general principle that repetition improves memory.

Several mainstream theories of the spacing effect (Ebbinghaus, 1885) run counter to this general principle, however. Two theories of importance are the deficient processing theory (Hintzman, 1974) and the new theory of disuse (Bjork & Bjork, 1992). Both theories imply that the encoding of familiar information is impaired relative to the encoding of novel information. In the context of the spacing effect, immediate repetitions of studied items are associated with better remembering than spaced repetitions. Of course, this inference is indirect, relying on the fact that memory improved *less* for immediate repetition than for spaced repetition. Inferior memory of a repeated item relative to a not-repeated item would provide a more compelling case that repeated study is associated with encoding costs. Indeed, the repetition decrement effect (Rosner et al., 2018) measures just such an effect; better recognition for a not-repeated target than a repeated target when preceded by an ignored prime. The repetition decrement effect provides direct evidence in support of deficient processing theories of the spacing effect.

A challenge associated with observing decrements in encoding for repeated items is that tests of memory, such as recognition, are sensitive to encoding of both the first instance and the second instance that make up a repetition. In many contexts, encoding of the second instance may be associated with an encoding decrement, but this decrement does not appear in memory performance because it is compensated for by memory of the first instance. If this is the case, then the repetition decrement effect may occur only when memory for the prime (the first instance) is especially poor. I assessed this issue in Chapter 2. In this chapter, I showed that robust prime encoding tasks such as naming the prime or answering a semantic question about the prime eliminated, and sometimes reversed, the repetition decrement effect (Experiments 2 and 3). These results are consistent with the idea that the repetition decrement effect is driven by the deficient processing of repeated target words, with robust encoding of the prime compensating for that deficient processing.

The position that the repetition decrement effect is driven by deficient processing (Bjork & Bjork, 1992; Ebbinghaus, 1885; Hintzman, 1976) implies that the same process may drive the repetition decrement and spacing effects. However, it was unclear whether a spacing effect would occur with the method used in our studies. To our knowledge, no prior studies have reported a spacing effect when the first encoding of a repeated event consists of a brief glance at an ignored prime. To address this issue, I pursued two additional issues with adaptations of the method used in the original repetition decrement studies: (1) Would spaced repetition relative to immediate repetition mediate the repetition decrement effect?; (2) Would spaced repetition improve memory relative to immediate repetition?

I examined the influence of spacing on the repetition decrement effect in Chapter 3. This chapter introduced an experimental design that contrasted memory for words repeated immediately with words repeated after a 10-minute delay. Immediate repetition produced a repetition decrement effect when prime words were ignored (Experiments 3a, 4a, and 4b), and a small positive repetition effect when primes were named (Experiment 3b). Spaced repetition produced a positive repetition effect regardless of the prime encoding task (Experiments 3a, 3b, 4a, and 4b), though this effect was largest when primes were named. Importantly, the interaction between repetition and spacing was significant for both prime encoding tasks. These results provide evidence that the repetition decrement effect is indeed sensitive to spacing, and preliminary evidence that a transient deficient processing mechanism causes both the repetition decrement and spacing effects (Ebbinghaus, 1885). However, there were two significant limitations to this conclusion. First, the spacing contrast in the hybrid design was limited to just two levels of spacing, comparing memory for words repeated after a couple of seconds to memory for words repeated after 10 minutes. Given that the spacing effect ought to increase with the delay between repetitions, evidence that the repetition decrement effect gradually decreases with the delay between repetitions is critical. Second, spacing for the two repeated conditions was confounded with retention interval, with the immediate repetition condition associated with a longer retention interval than the spaced repetition condition. This confounding did not allow a strong conclusion that a conventional spacing effect occurred in these experiments. These two limitations to the results of Chapter 3 were both addressed in Chapter 4.

The purpose of Chapter 4 was thus two-fold. First, I examined whether a computational model (Jamieson, Crump et al., 2002) that formalises the key elements of the new theory of disuse (Bjork & Bjork, 1992; Cuddy and Jacoby, 1986) could predict both the repetition decrement and spacing effects. Second, I examined the two limitations to the results of Chapter 3 described above, both from an empirical perspective and from the perspective of the computational model. Would deficient processing of repeated targets decrease gradually with increases in spacing, and can we measure a conventional spacing effect with our method?

The model developed in Chapter 4 was based heavily on Minerva-AL (Jamieson, Crump, & Hannah, 2012), which incorporates a process called discrepancy encoding. This process reduces the encoding of features in new events that are redundant with those already well-predicted by representations in long-term memory, similar in nature to Cuddy and Jacoby's (1982) deficient processing theory. Unlike the standard Minerva-AL model, however, the model presented in Chapter 4 calculated the discrepancy encoding with the use of a short-term buffer that introduces changes in retrieval strength as a function of retention interval (Bjork & Bjork, 1992). We called this model Minerva-ALB. The short-term buffer enabled Minerva-ALB to predict a variety of results presented in Rosner et al. (2018) and the earlier empirical chapters. Importantly, the model predicted that: (i) the repetition decrement effect would gradually decrease with increasing lag between repetitions; (ii) the repetition decrement would reverse to a repetition benefit with substantial increases in spacing; (iii) a conventional spacing effect would be observed. A new experiment confirmed these predictions. The repetition decrement effect dissipated gradually and was eliminated entirely when two or more prime-target pairs intervened between repetitions. Furthermore, recognition improved with each intervening trial, producing a continuous and robust spacing effect.

Together, the results point to a strong conclusion: that the repetition decrement effect is a direct measure of deficient processing (Cuddy and Jacoby, 1982; Ebbinghaus, 1885; Hintzman, 1976). This interpretation is consistent with the broader theory that the brain seeks to minimise the expenditure of attentional and encoding resources on information that is already represented in memory. I will now discuss how the present set of empirical results fits with the deficient processing theories presented in the introduction.

Implications of the Repetition Decrement Effect on Deficient Processing

The empirical chapters provide converging evidence that the repetition decrement effect is caused by the automatic and involuntary deficient processing of redundant information. This proposal is similar to that of Cuddy and Jacoby (1982) that learning is mediated by the retrieval of similar representations from memory. Specifically, they suggested that the encoding process minimises the re-encoding of representations that instead can be retrieved directly from memory. In this way, encoding of repeated events is often more akin to ‘remembering a solution’ rather than ‘solving a new problem’ (Jacoby, 1978).

Further examination of the results of Chapter 2 reveals an additional finding that supports this theoretical view. The relevant results are presented in

Figure 3 of Chapter 2, which summarises recognition memory for not-repeated primes, not-repeated targets, and repeated targets across three levels of prime encoding (ignore, name, semantic). Let us assume that recognition accuracy for not-repeated primes provides a reasonable estimate of the contribution of prime memory to the recognition of repeated prime-target pairs. If so, then the difference between recognition performance for not-repeated primes and repeated targets provides an estimate of the improvement in memory attributable to naming a word that has already been processed as a prime. Across the three levels of prime encoding we find that naming a repeated word produced a large benefit when preceded by an ignored prime (M = .206, SD = .116), a modest benefit when preceded by a named prime (M = .074, SD = .114), and a small benefit when preceded by a semantically analysed prime (M = .032, SD = .091). A one-way ANOVA of these difference scores was significant, $F(2,69) = 17.36$, $p < .001$, $\eta_p^2 = .335$. Put simply, when the encoding of a prime word was poor (i.e., in the ignore condition), there was a substantial benefit associated with seeing it again and naming it. Conversely, when the encoding of a prime was robust (i.e., in the semantic condition), there was only a modest benefit associated with seeing it again and naming it. These results fit with the view that deficient processing of repeated items is related to redundant representations recovered from memory, as proposed by Cuddy and Jacoby (1982) – well encoded primes lead to greater redundancy with target processing and smaller repetition gains in recognition performance.

This type of deficient processing account nicely explains how representations that can be retrieved from memory are effectively dropped from the encoding of a repeated target. In other words, when encountering a repeated target, one does not re-encode what can be retrieved effectively from memory. However, what this type of deficient processing account does not explain is why recognition of repeated targets can be worse than for not-repeated targets. Shouldn't recognition of a repeated target tap into the representations of both the prime and the target, and shouldn't the joint influence of these two representations on recognition be at least equal to that for not-repeated targets?

Although intuitively sensible, this interpretation of deficient processing theory assumes erroneously that the retrievability of a prime at the time of repetition in a prime-target pair is identical to its retrievability at the time of the recognition test, which may occur much later (10-15 minutes later in the experiments in this thesis). Of course, the accessibility of memories does not remain stable over time. Rather, the accessibility of a prime representation is likely to be much higher at the moment of repetition in a prime-target pair than in a following recognition test. Consequently, prime representations that are successfully retrieved upon onset of a target, and thereby result in diminished encoding for that target, may be unsuccessfully retrieved on the following recognition test. In this way, the joint accessibility of prime and target representations for repeated items at test can be lower than for a single not-repeated target representation. In any case, the new theory of disuse (Bjork &

Bjork, 1992), on which our modelling work was focused, provides a better intuitive framework for understanding how retrieval strength mediates encoding.

The new theory of disuse (Bjork & Bjork, 1992) suggests that the deployment of encoding resources is reactive in accordance with the need for additional encoding. Improvements in the storage strength of items are an inverse function of retrieval strength of those same items from memory. Although storage strength is permanent and stable, retrieval strength decays with time. Thus, with enough time and intervening study, it is possible to encode two copies of an item in memory robustly. This theory fits well with the notion that learning and memory are driven by a need for efficiency, since the encoding of highly retrievable items and features in memory is conservatively downregulated. Regarding the repetition decrement effect, when a prime is ignored there is little increase in storage strength but a significant increase in retrieval strength. Thus, when a repeated target is presented, it suffers from deficient encoding due to the highly retrievable representation of the prime, which attenuates further increases in storage strength. Since a poorly processed prime is unlikely to contribute much to the recognition of repeated target words at test, the normally adaptive learning system produces a maladaptive outcome: the repetition decrement effect. The boundaries of the repetition decrement effect are also sensible. First, a robustly encoded prime will increase storage strength in a manner that compensates for the deficient processing associated with high retrieval strength. Second, increasing the spacing of prime-target pairs diminishes retrieval strength and allows for a significant boost in storage strength when the repeated target is named.

In Chapters 3 and 4 I briefly discussed the established links between the new theory of disuse and neural phenomena such as repetition suppression (Xue et al., 2011; Zhao et al., 2015). Evidence of similar neural correlates for the repetition decrement effect would provide useful converging evidence that the same process drives the repetition decrement and spacing effects. The viability of the new theory of disuse for explaining the repetition decrement effect could be assessed further by replicating Experiment 3 from Chapter 2 while collecting fMRI data. An ideal result would show a causal link between the prime encoding task and: (i) the magnitude of neural repetition suppression, and (ii) performance on a subsequent recognition memory task for the repeated target words (see also Xue et al., 2011; Zhao et al., 2015). The combined results from behavioural, computational, and neuroimaging studies would then offer comprehensive evidence of the interaction between prime encoding, spacing, and recognition memory.

The Repetition Decrement Effect, Disfluency, and Event Segmentation

I have proposed that encoding is mediated by a fast assessment of retrievability of redundant representations already in memory. Although this proposal frames the repetition decrement and spacing effects in terms of encoding deficiencies for repeated items, our results can also be framed in terms of encoding benefits for novel events. Theories that focus on the role of prediction error (Henson & Gagnepain, 2010) and event segmentation (Zacks & Swallow, 2007) in human remembering offer an alternative framework for discussing the present results.

The predictive interactive multiple memory systems model (PIMMS; Henson & Gagnepain, 2010) provides an elegant and simple account of the repetition decrement effect. The model emphasises the bi-directional flow of information in memory. The bottom-up stream interprets incoming perceptual information, while the top-down stream generates predictions about incoming information. According to the model, learning is upregulated in response to prediction errors. In the context of the repetition decrement effect, the presentation of a repeated target produces a low level of prediction error. Little encoding then occurs because little learning is needed to generate an accurate representation of the repeated target. The presentation of a not-repeated target produces a high level of prediction error. Substantial encoding then occurs because substantial learning is needed to generate an accurate representation of the not-repeated target. Ideally, the purpose of this process is to reduce prediction error in the future, improving the ability of an organism to successfully predict its environment. This general idea also fits with the proposal that prediction error and medial temporal lobe activation is particularly high at the boundaries between events (Zacks & Swallow, 2007).

Conclusion

From an efficiency perspective, the human brain ought to be biased to allocate attention and learning resources to events that are not already represented in memory. Though the case for this bias is clear in the attention and performance literature, the case is less clear in the memory literature. However, the spacing effect does provide indirect evidence that learning is attenuated for events that are highly accessible in memory. I have proposed that the repetition decrement effect (Rosner et al., 2018) is a direct measure of a deficient processing mechanism that minimizes encoding of redundant information (Cuddy & Jacoby, 1982; Bjork & Bjork, 1992), and that contributes to the spacing effect in remembering (Bjork & Allan, 1970; Hintzman, 1976).

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