A retrieved context model of the emotional modulation of memory

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Abstract

Emotion enhances episodic memory, an effect thought to be an adaptation to prioritise the memories that best serve evolutionary fitness. But viewing this effect largely in terms of prioritising what to encode or consolidate neglects broader rational considerations about what sorts of associations should be formed at encoding, and which should be retrieved later. Although neurobiological investigations have provided many mechanistic clues about how emotional arousal modulates item memory, these effects have not been wholly integrated with the cognitive and computational neuroscience of memory more generally.

Here we apply the Context Maintenance and Retrieval Model (CMR, Polyn, Norman & Kahana, 2009) to this problem by extending it to describe the way people may represent and process emotional information. A number of ways to operationalise the effect of emotion were tested. The winning emotional CMR (eCMR) model reconceptualises emotional memory effects as arising from the modulation of a process by which memories become bound to ever-changing temporal and emotional contexts. eCMR provides a good qualitative fit for the emotional list-composition effect and the emotional oddball effect, illuminating how these effects are jointly determined by the interplay of encoding and retrieval processes. eCMR explains the increased advantage of emotional memories in delayed memory tests through the limited ability of retrieval to reinstate the temporal context of encoding.

By leveraging the rich tradition of temporal context models, eCMR helps integrate existing effects of emotion and provides a powerful tool to test mechanisms by which emotion affects memory in a broad range of paradigms.

Key words: Memory, Emotion, Arousal, Retrieved context models, Free recall.

1. Introduction

There is tremendous interest in the effect of emotional arousal on episodic memory. The literature generally agrees that moderate emotional arousal enhances item memory (Cahill & McGaugh, 1998; LaBar & Cabeza, 2006; Yonelinas & Ritchey, 2015). However, the circumstances in which it does so, and the mechanisms and models by which these effects are understood, might look unusual to a student of memory more generally. The mainstream human memory literature has traditionally tested memory within minutes of encoding because most functional manipulations do not dissociate immediate and delayed memory performance. By contrast, the research on emotional memory focuses on factors that influence delayed memory, and those are interpreted mostly in terms of prioritised storage. One reason for the appeal of that focus is that it suggests an interpretation in terms of the broader purpose of memory in guiding behaviour, and connections to an emerging set of rational, decision-theoretic accounts of the allocation of limited cognitive resources. In particular, emotionally-charged memories may be most relevant to fitness-relevant decisions later (Boureau, Sokol-Hessner, & Daw, 2015; Gershman & Daw, 2017), and therefore should enjoy priority for encoding and maintenance in the face of limited memory capacity. However, we argue this view is incomplete from both an empirical and a normative perspective.

Empirically, current models of emotional memory fail to predict when enhancement would be exhibited and when it would not. In particular, a simple prioritization explanation fails to account for situations in which emotion does *not* benefit memory, such as in free recall tests for pure lists of emotional and neutral stimuli (the emotional list-composition effect, described below); in immediate recognition tests for mixed lists of emotional and neutral stimuli (Dougal & Rotello, 2007; Sharot & Yonelinas, 2008); and in tests of associative memory (Bisby, Horner, Hørlyck, & Burgess, 2016; Madan, Caplan, Lau, & Fujiwara, 2012; Madan, Fujiwara, Caplan, & Sommer, 2017). Furthermore, while the emotional memory literature has so far marginalised the influence of the retrieval test, in other areas of memory there has been a recent emphasis on retrieved context models of memory, which emphasise a role for associations between items and context during both encoding and retrieval (Howard & Kahana, 2002a; Lohnas, Polyn, & Kahana, 2015; Polyn, Norman, & Kahana, 2009; Sederberg, Howard, & Kahana, 2008). 'Brain states' that change gradually with time (Manns, Howard, & Eichenbaum, 2007) are thought to provide the neurobiological substrate that implements the temporal context in such models, a view supported by recent evidence that temporal overlap functionally links neural representations of separate events (Cai et al., 2016; Rashid et al., 2016).

Apart from addressing these empirical considerations, retrieved context models suggest a more nuanced normative interpretation. Instead of simply ranking which individual items should be prioritized in isolation, the retrieved context models speak to what sorts of memory structures should be built by encoding associations among these items. Indeed, these associations themselves have a clear normative interpretation in that the item-context associations at the heart of retrieved context models mathematically correspond to a particular sort of world model for guiding utility-maximizing future choices (Gershman, Moore, Todd, Norman, & Sederberg, 2012). Retrieved context models also shed light on the distinct question of how memories will be prioritized for *retrieval* given the goals of the test context (DuBrow, Rouhani, Niv, & Norman, 2017). In decision making, such modulation of retrieval will promote consideration of particular (emotionally charged) outcomes of candidate actions, and are reminiscent of mechanisms independently proposed in the decision-making literature for rationally prioritized evaluation (Cushman & Morris, 2015; Huys et al., 2012; Lieder, Griffiths, & Hsu, 2018).

Here we reinterpret emotional memory effects in the framework of retrieved context models with the aim to explain how emotion enhances episodic memory through their already-established mechanisms, thus bringing the emotional memory literature more closely into the fold of the mainstream memory literature. Our aims are, first, to consider systematically the different ways in which emotion can be operationalised within the Context Maintenance and Retrieval Model (CMR); and second, to identify which constellation of mechanisms allow the extended model, emotional CMR (eCMR), to capture qualitatively key effects of episodic memory for emotionally arousing items.

FIGURE 1. Example negative (emotionally arousing) and neutral stimuli.

Note. Left. Ljubljana car crash 2013 © Dino Kužnik (CC-BY-2.0) Right. High Street cars in Narberth © Jaggery (cc-by-sa/2.0)

1.1 Existing models of emotional memory

The focus of the literature on emotional memory on delayed effects of emotion stems partly from the social value of understanding memory for key life events, that is, memories for experiences that define us as people (graduating from school, winning a competition) and as community members (weddings, funerals, flash-bulb memories for culturally important events). This remained a focus in the laboratory, where emotional experiences were operaitonalised by presenting participants with emotional words, pictures (**FIGURE 1**) and film clips, and memory for them was tested, typically, 24 hours to two weeks later. Another contributing factor for the focus on delayed memory is that the dominant model for emotional memory, the modulated-consolidation model (Cahill & McGaugh, 1998; McGaugh et al., 2000), is concerned with effects that manifest themselves after a few hours, but not before. Both the Modulated-consolidation model and the Emotional Binding account (Yonelinas & Ritchey, 2015) attribute all of the explanatory power to processes that occur in the hours and days after stimulus encoding is completed. The former model suggests that emotional arousal directly modulates the consolidation of memory traces, a process that can be triggered when emotional stimuli are encoded but equally when arousal is experienced after neutral stimuli are encoded. The latter account suggests that the arousal experienced at encoding results in attenuated forgetting because of reduced interference from less-common emotional experiences, without influencing consolidation. GANE (Mather, Clewett, Sakaki, & Harley, 2015) also proposes a neurobiological mechanism for the effect of arousal and arousal-attention interactions on protein synthesis after encoding is completed. All of these models fare well in accounting for the general finding that the effect of emotion on memory is more robust in delayed, compared to immediate, memory tests (reviewed in Yonelinas & Ritchey, 2015) and for the effects of stressors and neuromodulators on memory for pre-stress experiences (Shields, Sazma, McCullough, & Yonelinas, 2017).

Partly because of the dominance of the modulated-consolidation model, much of the theory-building work on human emotional memory has been conducted at the level of the neurobiological mechanism (Cahill & McGaugh, 1998; Mather et al., 2015; McGaugh et al., 2000), contributing to an emphasis on consolidation processes and testing memory post-consolidation. It remains much less clear how emotional memory enhancement relates to the processes associated with the cognitive and computational neuroscience of memory. This is because factors that have traditionally interested human memory researchers, such as the level of processing at encoding, or the nature of the memory test, are questions at the algorithmic, rather than the implementation level. Talmi's multi-factor mediation model (Talmi, 2013) discusses a number of known cognitive processes that allow emotion to influence encoding and retrieval, but like all other existing models of enhanced emotional memory, her model, too, did not yield quantitative predictions. No existing framework has been implemented quantitatively in a formal model

The Modulated Consolidation model considers encoding processes only in the sense that the consolidation of experiences that were arousing during encoding would be modulated (Cahill, Gorski, & Le, 2003). The only existing model of the cognitive processes that underlie emotional memory, Arousal-Biased Competition (ABC) theory (Mather & Sutherland, 2011), and its neurobiological sister model, GANE, dissect the influence that arousal has on competitive attention allocation at encoding, and offers a rich account for the multiple routes that lead to the prioritisation of particular stimuli, and how priority and its downstream memory consequences are influenced by systemic arousal. One of their key advantages is that they account for memory for emotional experiences not only in delayed, but also in immediate tests. This is important because memory for such experience is often enhanced in immediate tests. To take just three examples, when emotionally-arousing and neutral pictures were presented in the same study set, memory for emotionally-arousing pictures was greater than memory for neutral pictures when tested within an hour after encoding, as measured by free recall (Talmi, Schimmack, Paterson, & Moscovitch, 2007, see also Table 1), cued recall (Dolcos, LaBar, & Cabeza, 2004), and recollection (Kensinger & Corkin, 2004).

Existing models of emotional memory enhancement do not consider the possibility that emotion could have additional influences during the retrieval stage. This limits their ability to relate to some of the age-old themes in the study of human memory, such as the nature of the test (recall, recognition), assumed retrieval process (memory search, recollection, familiarity), and the context of the test (similar or different to the encoding context). The relative neglect of the explanatory power of retrieval mechanisms in these frameworks is incompatible with the mainstream human memory literature, where the consensus has long been that the conditions of retrieval often determine memory performance, as in the encoding specificity principle (Tulving & Thomson, 1973), transfer-appropriate processing (Graf & Ryan, 1990), and state-dependent memory (Smith & Vela, 2001) as well as their neural concomitant, instantiation (Danker & Anderson, 2010). Specifically in relation to emotion, the literature on mood congruency established that the retrieval context matters for emotional memory, with memory performance increasing when the mood at encoding and retrieval is consistent (Blaney, 1986). A study where participants encoded and retrieved stimuli with an emotional or a neutral context showed that this effect is not due solely to an emotional context at encoding or at retrieval, but to their match (Xie & Zhang, n.d.) Recent results also show that like neutral items (Cai et al., 2016), emotional items also have access to a drifting neural context (Rashid et al., 2016). Importantly, Rashid et al. showed that retrieving an emotional experience changes the way that a new experience is encoded, such that the two are functionally linked. It is reasonable, therefore, to expect that retrieval processes would play a role in enhanced emotional memory.

1.2 The potential of retrieved context models in research of emotional memory

Memory is better when context states at encoding and at retrieval are more similar (Howard & Kahana, 2002a; Smith & Vela, 2001). Some have attributed the recency effect to such contextual similarity (Glenberg & Swanson, 1986; Neath, 1993). The term "brain state" has been employed recently (Deco & Kringelbach, 2017; Manns et al., 2007; Tambini, Rimmele, Phelps, & Davachi, 2017) to describe mental context that evolves and changes gradually with time (Bower, 1967; Estes, 1955). By moving from random fluctuations in mental context to encoding-dependent changes in context, where context changes as a result of experiencing individual episodes or experimental stimuli, temporal context models have had much success in accounting for free recall dynamics, including recency effects (Howard & Kahana, 2002a; Sederberg et al., 2008). Famously, these models successfully account for contiguity effect - the propensity to recall contiguously items that have been encoded close in time to each other. The contiguity effect is important both because it contributes to our understanding of how memories are associated, and because it correlates with memory success (Sederberg, Miller, Howard, & Kahana, 2010). While the temporal context model based memory solely off of temporal associations (Howard & Kahana, 2002a), it has been clear for some time that semantic associations also contribute to retrieval success (Howard & Kahana, 2002b). CMR (Polyn et al., 2009) formally included non-temporal dimensions of context.

CMR is a computational model that makes predictions about memory dynamics in free recall and recognition. Built on the notion that the content of a memory is intimately tied to its associated (internal) context, CMR assumes that each presented item is associated with a context state, and that the brain's maintained state of context is updated by each presented or retrieved item. In this way, context changes slowly over time, as a recency-weighted sum of prior context states. During memory retrieval, the current context state is used to cue recall or recognition. CMR includes two dimensions of items' non-temporal context, which are known to contribute to recall dynamics. Semantic context refers to the pre-experimental associations between studied items. Source context refers to experimental associations between studied items, resulting from specific encoding operations performed during the study of some items but not others. In Polyn's et al.'s first simulation this referred to judging the size of half of the items in the list and the animacy of the other half. CMR also assumed that a switch between these two source contexts disrupts the temporal context, such that the temporal context states between two items separated by a task switch were less similar. The model was supported by evidence of clustering around the source context, concomitant with reduced reliance on temporal context (Polyn, Erlikhman, & Kahana, 2011; Polyn et al., 2009). Because similarity between the study and test contexts on any dimension can help retrieve a studied item, this generalisation enables CMR to explain the increased tendency to recall contiguously items that are similar to each other on non-temporal dimensions.

The fact that CMR considers the memory consequences of the similarity between encoded experiences beyond temporal context alone is important for the purpose of accounting for the effects of emotion on memory. If emotional items are represented as having a higher degree of similarity to one another on an 'emotional context' dimension, CMR should predict that participants will cluster their recall around the dimension of emotionality. There is, in fact, empirical evidence for emotional clustering of free recall. In one study participants encoded three pure lists of emotional, random-neutral and related-neutral items, and received a single, surprise final free recall test after all three lists were encoded (Talmi, Luk, McGarry, & Moscovitch, 2007). Participants who clustered their recall around list categories more than others – those who, at the extreme end, recalled the pure lists that they studied separately - exhibited a smaller emotion-enhanced memory. In that study, temporal and emotional context effects were confounded because the three item categories were studied in three separate lists, but emotional clustering appears also in free recall of mixed lists that contain both emotional and neutral items. For example, Barnacle et al. (Barnacle, Montaldi, Talmi, & Sommer, 2016) presented participants with mixed lists of emotional and neutral pictures which were equally semantically related, and found clustering around the emotional/neutral category; the degree of clustering predicted memory performance. Long and colleagues (Long, Danoff, & Kahana, 2015) presented participants with mixed lists of words, some of which were negative and some positive, and found that participants tended to retrieve positive items after other positive items, and similarly for negative and neutral items. Emotional clustering was observed even when pre-experimental semantic associations between words (obtained through latent semantic analysis scores) were taken into account. In another study, the transition probability from pleasant items to pleasant items, and from unpleasant items to other unpleasant items, was higher than the transition from neutral to neutral items (Siddiqui & Unsworth, 2011). These findings suggest that participants retrieve the emotional context of recalled items, which updates the test context and becomes part of the next retrieval cue.

1.3. The emotional Context-Maintenance and Retrieval (eCMR) model

Here we generalize the CMR framework to examine hypotheses regarding the emotional modulation of memory. We take advantage of CMR's representations along multiple stimulus dimensions to incorporate emotionality of presented items. In this section, we consider systematically which aspect of CMR may be influenced by emotion. This empirical literature led us to consider in detail two nested variants of our extended model, eCMR, which is described formally in section 2.2 and schematically in **FIGURE 2**,. The *category variant* represents certain items as belonging to an emotional category, and others as belonging to a neutral category. We also consider predictions from two *attention-category* variants of the model, in which emotional arousal has an additional impact: during encoding, emotionally-arousing items attract more attention than neutral items during encoding. Overall, the attention-category variant of eCMR emerges as a winner, able to capture a number of key emotional memory phenomena.

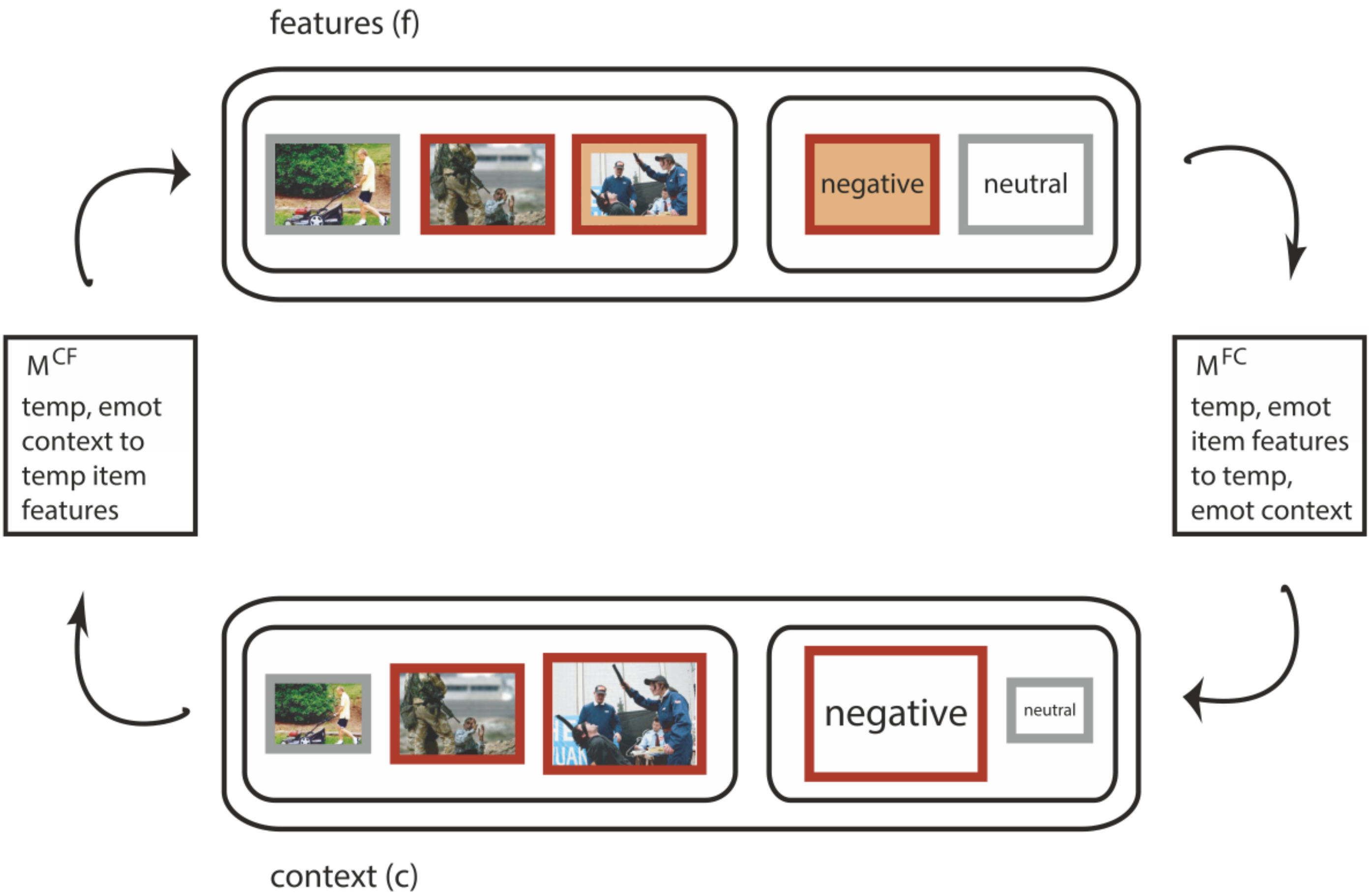


FIGURE 2: A schematic of item and context representations in eCMR.

1.3.1 The category variant of eCMR

In CMR (Polyn et al., 2009) each item is represented with three types of features: item, semantic, and source. The item features are typically uniquely set for each item. Semantic features of the items are incorporated into the association matrix between temporal context and item features, under the assumption that semantically related items co-occur in similar contexts over time (Rao & Howard, 2008). Each item also has a 'source' feature corresponding to aspects of the stimulus that are common to many items in the study set. This was introduced in CMR to represent the orienting task that was associated with each item during encoding, although Polyn and colleagues recognized that source features could be internal – unique operations that participants may engage in during the encoding of certain stimulus types. When items are encoded their temporal and source contexts are updated, resulting in increased similarity between the temporal contexts of items that are encoded close to each other in time, as well as increased similarity between the source contexts of items that were encoded with the same orienting task. When a particular item is recalled, it will promote the recall of items with similar semantic, temporal, and source context dimensions.

Consider the emotional items that are prevalent in emotional memory experiments, such as a picture depicting a car crash (**FIGURE 1**). In the *category variant* of eCMR the 'source' item feature implements its emotionality, such that it defines certain items as 'emotional' and others as 'neutral' (graded coding is entirely feasible but for the purpose of the simulations we present here, we defined items in a binary way as 'emotional' or 'neutral'). Just as in CMR, where items that share source context promote each other's recall, in eCMR items that share emotional context will also promote each other's recall.

The temporal and semantic features are represented in exactly the same way in eCMR as in CMR, but the strength of semantic associations operationalise both the semantic similarity between items, based on their shared conceptual and thematic relationship, and their emotional similarity. By definition, emotional stimuli belong to the same conceptual category (e.g. 'negative experiences'). It is established that emotional stimuli are often thematically similar; for example, the words 'bomb' and 'starvation' will co-occur within a story of war. Other factors that may increase the thematic similarity between emotional items is that they may be construed as socially more 'distant' (Trope & Liberman, 2003), or share affordances (Greene, Baldassano, Esteva, Beck, & Fei-Fei, 2016), such as approach (towards positive picture content) and avoidance (away from negative picture content). Emotional stimuli may also be similar because they trigger the same feelings, embodied in a myriad of peripheral physiological processes (Bradley, Lang, & Cuthbert, 1993). These differences between emotional and neutral stimuli explain why randomly-selected emotional pictures are rated as more similar to each other than randomly-selected neutral pictures (Talmi & Moscovitch, 2004). The increased similarity between emotional stimuli has memory consequences, explaining part of the recall advantage of emotional items (Talmi, Luk, et al., 2007; Talmi & Moscovitch, 2004). It is important to note that some experiments go to great lengths to equate the pre-experimental similarity of emotional and neutral stimuli (Kensinger, 2009b; Schmidt & Saari, 2007; Sommer, Gläscher, Moritz, & Büchel, 2008), including the key experiment we simulate in section 2 (Talmi et al., 2007). However, even when pre-experimental similarity is controlled emotional items will still end up, in effect, more similar to each other in eCMR because during encoding they will be bound to a shared emotional context.

Lastly, a critical aspect of CMR is the assumption that the temporal context is disrupted whenever the orienting task changes during encoding (Polyn et al., 2009). While the task Polyn and colleagues used is akin to task-switching paradigms, mixed lists of emotional and neutral items may more closely resemble cue-shift paradigms, where the task remains the same, but the cue that lets participants know which task to execute varies. Just as an animacy-judgment task could be cued by both a circle and a square, the operations that emotional items trigger are cued by items with different content. Importantly, both task-switches and cue-switches slow reaction times in the post-shift trials (Schneider & Logan, 2006), a result that may indicate that both type of switches could be modelled as disrupting the temporal context. As we will see, how much the temporal context is disrupted when emotional and neutral items alternate substantially influences model predictions. In keeping with CMR, in section 2 we assume that such disruption occurs, albeit subtly, while in section 5 we examined the impact of a substantial disruption. In summary, the *category variant* of eCMR in Simulation 1 is very similar to CMR but uses emotionality as an internal source feature of items and a lower level of temporal context disruption with a change in task.

1.3.2 The attention-category variant of eCMR

It is established that emotionally-arousing stimuli attract more attention than neutral stimuli. Arousal enhances attentional selection, modulation and vigilance (Golomb, Turk-Browne, & Chun, 2010). For example, autonomic arousal or visual attention to objects that have been previously presented on emotional backgrounds is enhanced even when those emotional backgrounds are no longer there (Ventura-Bort et al., 2016). Allocation of attention to emotional stimuli is driven by the amygdala and results in enhanced sensory processing downstream, a mechanism which is distinct from (direct) stimulus-driven effects or strategic top-down effects (Pourtois, Schettino, & Vuilleumier, 2013). The mechanism involves amygdala-dependent activation of the locus coeruleus, where noradrenergic neurons increase the neural gain throughout the brain through their wide-ranging projections (Mather et al., 2015). Based on the consensus in the literature eCMR assumes that stimuli with an 'emotional' item feature attract attention preferentially, although of course, in reality there is variability in the degree of attention allocated to specific emotional stimuli.

In retrieved context models such as CMR, CMR2 and TCM-A (Lohnas et al., 2015; Polyn et al., 2009; Sederberg et al., 2008), increased attention to early stimuli in the study list has been implemented by strengthening the associations between items and their temporal contexts. This is accomplished by modulating the step-size or learning rate parameter on encoding these items, itself a standard mechanism to capture competitive attentional effects in associative learning theories more generally (Dayan, Kakade, & Montague, 2000; Pearce & Hall, 1980). Attention at encoding improves recall; for example, late positive potential at study, an ERP sensitive to stimulus-driven attention, covaries with memory success (Chen, Lithgow, Hemmerich, & Caplan, 2014). In retrieved context models the tighter binding of items to their context likewise increases the competitiveness of items during retrieval. What distinguishes the attention-category variant of eCMR from the category variant of eCMR is that it represents the increased attention to emotional items at encoding through their increased binding to their context during encoding. Below, after we describe the model more formally, we also discuss how this attentional assumption differs from past model variants.

The implementation of attention in eCMR as increased strength of item-context associations is based on evidence that emotional stimuli are more tightly associated to their context. According to the priority-binding hypothesis (MacKay et al., 2004) emotional items are bound more strongly to their presentation context than neutral items. This assertion is evident in that emotional items escape the attentional blink more readily – namely, they are more likely to be reported when presented in a rapid serial visual stream close to a target stimulus – because they are bound better to their encoding context (Anderson, 2005; Mackay, Hadley, & Schwartz, 2005). Similarly, in the object-based framework attention is allocated preferentially to features perceived as belonging to the same emotional object, driving increased binding of emotional object features (Mather, 2007). The object-based framework is supported by evidence for increased memory for the source of within-object features, such as the font colour and screen location of taboo words (MacKay & Ahmetzanov, 2005). In summary, the *attention-category* variant of eCMR in Simulation 2 encapsulates the *category variant* but also makes one additional assumption - that emotional items attract more attention, operationalised as increased strength of their binding to their encoding context. After we present the model formally we discuss the different ways that increased binding to the context could be implemented.

To preview how this eCMR variant works, note that the only difference between this and the *category-only* variant is that emotional stimuli are attended preferentially when they are presented. Therefore, they are more strongly bound to their context at encoding, compared to neutral items, and – when the model simulates recall of mixed lists – they are more strongly associated to the context at the beginning of the memory test, increasing the likelihood that recall would begin with an emotional, rather than a neutral item. Encoding emotional items renders the source context of an immediate test more emotional than it would be after the encoding of neutral items; the number of emotional items in the list, particularly at the late serial positions, will influence the emotionality of the test context. An emotional context will facilitate recall of emotional items. Likewise, recalling an emotional item promotes the recall of another emotional item, both because they share their source context, and because during encoding, the switch to an emotional source disrupted the temporal context, reducing the likelihood that previously- or subsequently-encoded neutral items would be retrieved on the basis of temporal contiguity. Although many of the experiments simulated here control for semantic relatedness, another reason that emotional items promote each other's recall is that they are often also more closely related to each other semantically than other items. Each recall of an emotional item additionally updates the temporal context, moving it yet further away from the temporal context that pertained during the encoding of neutral items, and therefore further hindering their recall. This variant of eCMR thus describes emotional memory enhancement as multiply determined, in keeping with the multiple factors previously posited to contribute to this effect (Talmi, 2013).

1.4 Overview of aims and objectives.

Thus far we have delineated, in broad terms, the limitation of previous models of emotion-enhanced memory and the promise of an extension of CMR – eCMR – to account for critical effects of emotion on episodic memory. Our overall aim in this paper is to illustrate how this can be achieved on a qualitative level for all effects, rather than fit the nuances of any particular data set. We chose this approach because a more precise fit would most likely require a rigorous parameter search for each data set. With different parameter values for each data set, this might obfuscate whether the model can only capture each of the effects within restricted ranges of specific parameter values, or can capture all effects simultaneously. By comparing model predictions on a qualitative level we could keep constant more model parameter values. In fact, we set as many parameters possible based on a previous algorithmic search for best-fit parameters in free recall (Polyn et al. 2009). For other parameters with changed values, we nonetheless kept most values constant across simulations. Within each section parameter values only change to simulate the study-test retention interval and the increased surprise occasioned by the presentation of an oddball in the list (Tables 1-2). Across sections we only varied the relative reliance on semantic associations, because section 2 used more cohesive study sets.

In section 2 we use the *category-only* and *attention-category* variants of eCMR to simulate the emotional list composition effect: the advantage of emotional over neutral items in the recall of mixed lists, and their diminished advantage in the recall of pure lists. While this is a relatively simple effect, described by four data points that correspond to average free recall, it has so far evaded explanation by existing models of emotional memory. We show that the *attention-category* variant captures this effect qualitatively, while the *category-only* variant failed to do so. By probing the retrieval dynamics in eCMR we show how the model helps reveal the multiple mechanisms that give rise to this effect and render it so robust. In section 3 we use the winning, *attention-category* variant of eCMR to compare immediate and delayed recall of mixed lists, where the pattern of results reported in the literature on delayed emotional memory is less familiar in the literature of memory modelling. In section 4 we show that eCMR predicts state-dependent memory effects, although they were very subtle with the parameter values that we selected here. In Section 5 we examine a particularly challenging effect for eCMR, the emotional oddball effect. The attention-category variant of eCMR can capture the effect by assuming that more attention is allocated to the oddball and that it disrupts the temporal context of encoding more than a similar emotional item in mixed lists, where such items are more frequent. With these assumptions in place eCMR captures key empirical results.

TABLE 1. Variable parameter values in Simulations 1-5.

Parameter	*Polyn et al. 2009*	*1*	*2*	*2R*	*2O 2E 2N*	*3*	*3D*	*4*	*4A*	*4AD*
β^{temp}_{rec}	*.51*	*.51*	*.51*	*0*	*.51*	*.51*	*0.4*	*.51*	*.51*	*.51*
β^{emot}_{rec}	*.588*	*.588*	*.588*	*0*	*.588*	*.588*	*.588*	*.588*	*.588*	*.588*
L^{CF}_{tw}	*1*	*.3*	*.3*	*.3*	*.3*	*1*	*.2*	*.5*	*.5*	*.5*
L^{FC}_{wt}	*.898*	*.898*	*.898*	*.898*	*.898*	*.898*	*.334*	*.898*	*.898*	*.898*
d	*.776*	*.3*	*.3*	*.3*	*.3*	*.3*	*.3*	*.3*	*.3*	*.776*
β_{dist}	--	*.976*	*.976*	*.976*	*.976*	*0*	*.776*	*.976*	*.976*	*.976*
Φ_{emot}	--	*1*	*1.25*	*1.25*	*1*	*1.25*	*1.25*	*1.25*	*3*	*3*
β_{emot}	--	--	--	--	*.976*	--	--	--	--	

Note: Only parameter values that varied across the simulations in this manuscript are listed here; see Table 2 for fixed parameter values. Superscripts to L: CF = context to item; FC: item to context; Subscripts to L: tw = temporal context to item; wt = item to temporal context. emot = emotional, rec = recall, dist = distractor.

TABLE 2. Fixed parameter values in simulations.

Parameter	Value
$\boldsymbol{\beta_{enc}^{temp}}$	0.4
$\boldsymbol{\beta_{enc}^{emot}}$	0.588*
$\boldsymbol{\gamma^{FC}}$	0.898*
$\boldsymbol{s}$	2.780*
η	0.159*
τ	0.174*
$\boldsymbol{\Phi_s}$	1.070*
$\boldsymbol{\Phi_d}$	0.981*
κ	0.11
λ	0.45

Note: *Values were inherited from Polyn et al. 2009.

2. eCMR captures the emotional list composition effect

The list composition effect is an umbrella term that refers to an interaction between the typicality of an individual item to be encoded and the global composition of the encoding list (McDaniel & Bugg, 2008). This manipulation could be executed by selecting atypical items that attract special encoding processes because of their own unique attributes, for example those that are unusual, complex, or bizarre; or it could be due to experimental instructions to process a subset of items in a special way, for example by enacting or generating a subset of items while others are silently read. 'Unusual' items are recalled better when they are encoded in the same list as the 'standard' items, but their advantage is minimised or even eliminated when each item type is encoded separately, in a pure list (McDaniel & Bugg, 2008). This effect is unique to free recall; in recognition memory tests memory for unusual items is better than memory for standard items (McDaniel & Bugg, 2008).

The list composition effect is related to the list-strength effect (Ratcliff, Clark, & Shiffrin, 1990) – the finding that spaced repetition of some of the items gives them a larger advantage in free recall memory tests when they are presented in a mixed list with non-repeated items, compared to a situation where repeated and non-repeated items are presented in pure lists. While the repetition is considered to make items 'stronger', and is therefore akin to the 'strength' of unusual items, the effects of spaced repetition may not be the same as the effect of unusualness. While memory consequences of unusualness are thought to be due to the attention and elaboration of unusual stimuli (McDaniel & Bugg, 2008), longer or deeper processing of standard items does not give rise to the list strength effect (Malmberg & Shiffrin, 2005). Despite these differences, the effects resemble each other also in that the list-strength effect also disappears in recognition memory tests (Shiffrin & Steyvers, 1997).

Because emotional stimuli have unique attributes and attract unique processing operations, it is unsurprising that emotion also gives rise to an emotional list composition effect in free recall. Mixed lists operationalise telling a friend about experiences that include some emotionally arousing aspects: a colleague made an infuriating insinuation, the coffee machine was broken, and a favourite colleague announced they were leaving during an otherwise unremarkable work day. Pure lists operationalise telling someone about a more difficult day, with many emotionally arousing aspects: a child broke their arm, we got a ticket while rushing to school, and spent the day in hospital. While the recall advantage of emotional stimuli is robust in mixed lists, it is smaller, and sometimes eradicated, in pure lists. Table 3 lists some demonstrations of that effect in the literature; note that the pattern is clearest when emotional stimuli are highly arousing (i.e. pictures or taboo words), and when the semantic relatedness of stimuli is equated. Most of these used free recall, so the influence of the retrieval test on this effect should be studied further.

TABLE 3. The emotional list composition effect.

	Mixed		*Pure*	
	Emotional	*Neutral*	*Emotional*	*Neutral*
(Dewhurst & Parry, 2000)***(Exp 1 and 2)*** [ac]	*49*	*48*	*55*	*35*
(Hadley & MacKay, 2006)***(Exp 2)*** [b]	*45*	*36*	*44*	*45*
(Talmi, Luk, et al., 2007)***(Exp 1)***	*72*	*57*	*71*	*66*
(Watts, Buratto, Brotherhood, Barnacle, & Schaefer, 2014)	*37*	*25*	*35*	*30*
(Barnacle, 2015)***(Chapter 6)*** [R]	*61*	*48*	*53*	*56*
(Barnacle et al., 2016)[R]	*59*	*58*	*64*	*48*
(Barnacle, Tsivilis, Schaefer, & Talmi, 2017)[R]	*63*	*41*	*57*	*53*
(Talmi & McGarry, 2012)***(Exp1)*** [R]	*56*	*31*	*56*	*42*
(Talmi & Moscovitch, 2004)***(Exp 2B and 3)*** [R]	*27*	*33*	*22*	*36*
(Talmi, Luk, et al., 2007 ***(Exp 2A and 2B)*** [R]	*58*	*47*	*57*	*56*
(Talmi, Luk, et al., 2007 ***(Exp 4)*** [R]			*61*	*67*
(Sommer et al., 2008)[P]			*42*	43

Note. Other than when indicated, all data refers to free recall tests using picture stimuli. Data in the table was extracted from the figures when the averages were not reported in the text. [a] *Emotional word stimuli.* [b] *taboo word stimuli.* [c] *Corrected "Remember" responses.* [R] *stimuli were controlled for semantic relatedness.* [P]Arousing and non-arousing items, data kindly provided by the author.

The emotional list composition effect is outside the scope of the modulated consolidation model and the emotional binding account, because it is obtained in immediate memory tests. It is also difficult to account for the effect using GANE or ABC theory because of evidence that emotional items receive extra attention in both mixed and pure lists (Barnacle & Talmi, 2016). For example, when participants viewed stimuli under divided attention their performance on the concurrent auditory choice reaction time task was poorer when they viewed emotional, compared to neutral pictures in both pure and mixed lists (Talmi & McGarry, 2012). In another study EEG was recorded while participants encoded the pictures. Electrophysiological markers of attention and working memory were increased when participants viewed emotional, compared to neutral, pictures in both pure and mixed lists (Barnacle, Tsivilis, Schaefer, & Talmi, 2018). In both of these studies, the list composition did not modulate the attention towards emotional stimuli. Indeed, this appears to be a common feature across list composition manipulations, where increased attention to unusual items also is not modulated by list composition (reviewed in McDaniel & Bugg, 2008). Furthermore, in a study where we scanned participants with fMRI during encoding in the emotional list-composition paradigm we found no evidence for reduced attention to neutral stimuli or increased attention to emotional stimuli in mixed, compared to pure lists (Barnacle et al., 2016). These empirical findings motivated us to assume, in Simulations 1-2, that increases in attention to emotional compared to neutral items were equivalent in magnitude across pure and mixed lists. Taken together, because emotional stimuli are more elaborated than neutral stimuli, and because elaborated stimuli produce list composition effects even when they are not emotional, all list composition effects may share some of their mechanisms. By contrast, the emotional list composition effect is probably less related to the list-strength effect, which depends on spaced repetition but is unaffected by elaboration.

Below we describe two ways of operationalising the impact of emotion on CMR based on the considerations discussed in the previous section. The test for each model variant is its ability to mimic qualitatively the empirical pattern of results depicted in ***Figure 3***, rather than reproduce the numbers themselves. Specifically, we were looking to capture the interaction between emotion and list composition, where emotion enhances recall in mixed but not pure lists. After we describe the simulations of average recall we describe the dynamics of recall in the winning model variant, and then describe additional empirical data that supports the conclusion that the emotional list composition effect depends on multiple aspects of encoding and retrieval dynamics.

2.1 A description of the empirical data from Talmi et al., 2007

We simulated the average recall data from the emotional and related-neutral conditions in Talmi et al., 2007, Experiment 2. Details of the methods of that experiment are presented in **APPENDIX 1**. The semantic coherence of the stimuli used in that experiment was matched by selecting neutral items that depicted domestic scenes, and selecting emotional and neutral stimuli matched on their average inter-relatedness based on a separate rating study.

The results of this experiment, which are depicted in ***Figure 3***, produced the pattern we refer to in this paper as the emotional list-composition effect. Emotional stimuli were recalled better than neutral ones in the mixed list condition, but their advantage was diminished, and here non-significant, in the pure list condition. Qualitatively similar results were replicated in subsequent studies (see Table 3). The pure list condition, which is rarely employed in research on emotional memory, offers a unique insight about the mixed-list results. In effect, the pure list condition could be considered a control condition, against which the mixed list condition could be interpreted. Described in this way, the data suggest that the emotional memory advantage in mixed lists stems entirely from a decrease in memory for neutral items in the mixed-list (compared to the pure-list) condition rather than from an increase in memory for emotional items in that condition. In fact, in this experiment memory for emotional items was equivalent across pure and mixed lists. Across experiments with emotional and neutral stimuli we always find a decrease in memory for neutral items presented in mixed (compared to pure) lists, while an increase in memory for emotional items in mixed (compared to pure) lists is not always significant. List composition effects are mostly described by reference to the difference between items (emotional and neutral, usual and unusual) within the same (pure or mixed) list (e.g. predictions 8 and 9 in Table 2 in McDaniel and Bugg, 2008). The conditions that give rise to an advantage of emotional and unusual items in mixed, compared to pure, lists await further research. To gain better understanding of memory performance in the list composition task the figure includes a second experiment (Barnacle et al., 2018).

To fully understand the interaction between attention to emotion at encoding and the retrieval machinery of eCMR we analysed the types of transitions the model made between successive recalls in the empirical data (from Talmi et al., 2007 and Barnacle et al., 2018). Power was slightly higher in the Barnacle et al.' s study because there were four lists in each condition there compared to one list in the Talmi et al. study. First, we examined the proportion of transitions made based on temporal associations in pure lists, and how those were affected by category membership (emotional/neutral). ***Figure 3*** depicts contiguity effects in the recall of pure lists, plotting the probability of recalling each item as a function of the lag from the currently-recalled item at lag=0 (Howard & Kahana, 1999). It is clear that these curves are very noisy; the number of lists they are based on is very small compared to other studies of recall dynamics in the literature. To increase power we collapsed the across serial positions and computed temporal clustering scores (Polyn et al., 2011, 2009). For each recall transition, we considered the absolute lag of that transition against the distribution of absolute lags from not-yet-recalled items, assigning it a score from 0 to 1, where 1 reflects that the transition was the smallest absolute lag possible. Thus, overall higher temporal clustering scores reflect recall organisation with greater influence from temporal associations, and 0.5 the baseline level expected by chance (**TABLE 4.**). Temporal clustering was greater than chance in the more powerful Barnacle et al. dataset (emotional lists: $t(24)=3.27$, $p<0.01$; neutral lists: $t(24)=2.15$, $p<0.05$) but not in the Talmi et al. dataset (emotional lists: $t(23)=1.11$, $p=.27$; neutral lists: $t(23)=1.91$, $p=.06$). In neither was there a significant difference between conditions (Talmi et al. $t<1$, Barnacle et al., $t<1$). The slopes of the lag-CRP curves were relatively shallow and the clustering scores were nevertheless low, suggesting limited reliance on the temporal context during recall in that experiment. Three aspects of the task might have contributed to this. First, each experimental list was preceded and followed by two buffers, and a distractor task was interpolated between study and test, removing the majority of primacy and recency influences. Second, because the majority of the lists in the experiment were semantically related, increasing reliance on semantic and emotional dimensions of context compared to the temporal context. Our choice of model parameters was informed by the relative contributions of temporal organization and emotional organization to recall dynamics.

Next, we examined transitions in the recall of mixed lists (**TABLE 4.**). Transitions that were based on temporal contiguity within the same category, namely, the tendency to retrieve an emotional (neutral) item that was encoded close in time to another emotional (neutral) item, was greater than chance (Talmi et al. $t(22)= 2.49$, $p=.02$; Barnacle et al. $t(23)=2.72$, $p=.01$). This was not the case for temporal clustering between categories, which was at chance (Talmi et al. $t<1$, Barnacle et al., $t<1$). We also examined the emotional clustering score, defined as the proportion of transitions made to the same emotional category out of all transitions. Thus, recall of an item from either emotional context (neutral or emotional) will support recall of items from the same emotional state, regardless of any temporal contiguity. Transitions based on shared emotional context were, again, more likely than what is expected at chance (Talmi et al. $t(23)= 3.31$, $p<.01$, Barnacle et al. $t(23)=3.77$, $p<.001$).

2.2 A formal description of eCMR

We begin by describing the assumptions of eCMR that follow directly from those of CMR, before turning to those unique to a model that incorporates the emotional aspect of memory. In eCMR, each studied item i has an associated feature vector $\mathbf{f}_i$ and context vector $\mathbf{c}_i$ which interact through the association matrices M^{FC} and M^{CF}. When an item is presented to the model, this activates its feature vector $\mathbf{f}_i$. This vector is a concatenation of item features ($\mathbf{f}_i^{item}$) and emotional features ($\mathbf{f}_i^{emot}$), analogous to the definition of item and source features in CMR. For simplicity, each temporal context and emotional context sub-region of $\mathbf{f}_i$ has a localist, orthonormal representation.

This feature vector then creates an input to context. This input to context, $\mathbf{c}_i^{\mathbf{IN}}$, is defined as:

$$\mathbf{c}_i^{\mathbf{IN}} = M^{FC}\mathbf{f}_{i.} \tag{1}$$

Like the item vector, the context vector is a concatenation of temporal and emotional representations, and each of temporal and emotional context is updated separately and normalized to have unit length. Next, this input to context, $\mathbf{c}_i^{\mathbf{IN}}$, is used to updated the current context state, $\mathbf{c}_i$:

$$\mathbf{c}_i = \rho_i \mathbf{c}_{i-1} + \beta \mathbf{c}_i^{\mathbf{IN}} \tag{2}$$

where β defines how much context is updated for each presented item, and takes on a separate value for the temporal and emotional sub-regions (β_{enc}^{temp} and β_{enc}^{emot}, respectively). This arrangement allows the emotional context to drift at a different rate than the temporal context. Given that physiological arousal can give rise to slow systemic effects, this was seen as a desirable property. The β parameters are fixed to the same value each presented item. ρ_i is determined separately for each sub-region to normalize the level of contextual activation to have unit length (see Howard and Kahana 2002 for a more detailed discussion of the importance of this step):

$$\rho_i = (1 + \beta^2[(\mathbf{c}_{i-1} \cdot \mathbf{c}_i^{\mathbf{IN}})^2 - 1])^{1/2} - \beta(\mathbf{c}_{i-1} \cdot \mathbf{c}_i^{\mathbf{IN}}). \tag{3}$$

As each item is presented, the associative matrices (M^{FC} and M^{CF}) are updated according to a standard Hebbian learning rule, such that:

$$\Delta M^{FC} = \mathbf{c}_i \mathbf{f}_i^{\mathrm{T}},$$

$$\Delta M^{CF} = \phi_i L^{CF} \mathbf{f}_i \mathbf{c}_i^{\mathrm{T}}. \tag{4}$$

For early list items, eCMR assumes a primacy gradient of attention such that the change in M^{CF} is scaled by ϕ_i, which is greatest for early list items and decreases exponentially to an asymptotic value over the course of list presentation:

$$\phi_i = \phi_s e^{\phi_d (i-1)} + 1, \tag{5}$$

where ϕ_s and ϕ_d are model parameters. L^{CF} in Equation 4 is a matrix that allows CMR to scale the magnitude of source associations relative to temporal associations. L^{CF} has four sub-regions, corresponding to each of the 4 possible association types:

$$L^{CF} = \begin{bmatrix} L_{tw}^{CF} & L_{ts}^{CF} \\ L_{sw}^{CF} & L_{ss}^{CF} \end{bmatrix}. \quad (6)$$

In the subscript, the first term refers to the context type (temporal (t) or source (s), i.e. emotional), and the second term refers to the feature type (again, temporal (w) or source). For simplicity, only the temporal feature terms are set to non-zero values: the emotional context to temporal feature associations, L_{sw}^{CF}, is a model parameter; the temporal context to item feature associations, L_{tw}^{CF}, was fixed at 1 for Polyn et al., 2009, but we consider other values for this parameter, as described below.

In a similar way, M^{FC} also has 4 sub-components (i.e. those starting with w), but again only the temporal feature terms are set to non-zero values:

$$L^{FC} = \begin{bmatrix} L_{wt}^{FC} & L_{ws}^{FC} \\ L_{st}^{FC} & L_{ss}^{FC} \end{bmatrix}. \quad (7)$$

In M^{FC} the relative contribution of the updated experimental associations to the pre-existing associations is controlled by the parameter γ^{FC}:

$$M^{FC} = (1 - \gamma^{FC})M_{pre}^{FC} + \gamma^{FC}\, M_{exp}^{FC}, \quad (8)$$

whereas the pre-experimental and experimental components of M^{CF} do not have this trade-off:

$$M^{CF} = s\, M_{pre}^{CF} + M_{exp}^{CF}. \quad (9)$$

Given that the semantic associations are stored in M_{pre}^{CF} as described above, the s parameter thus controls the relative contribution of semantic associations to the experimentally formed (temporal and emotional) associations.

In the item layer, the emotional source units are set solely based on whether the currently presented item is emotional or neutral. In the context layer, the emotional source units are a recency-weighted sum of past emotional states, such that if emotional items were presented in the more recent past, then the emotional context unit will have a greater strength.

After all list items are presented, if there is an end-of-list distractor, it is simulated in the model by again updating $\mathbf{c}$ according to Equation 2. In this case, the distractor is a single item and updates temporal context with value β_{dist}. Like the disruption to temporal context between types of emotional context, this disruption item is not incorporated into the association matrices and cannot be recalled.

At the time of recall, cuing with the context associated with the final list item i, $\mathbf{c}_i$, retrieves a vector $\mathbf{f}_r^{\mathbf{IN}} = M^{CF}\mathbf{c}_i$. To determine which item the model recalls, $\mathbf{f}_r^{\mathbf{IN}}$ serves as the input to a leaky, competitive accumulation process (Usher & McClelland, 2001) whose value at time step t is determined by

$$\mathbf{x}_t = (1 - \tau\kappa - \tau\lambda\mathbf{N})\mathbf{x}_{t-1} + \tau\mathbf{f}_r^{\mathbf{IN}} + \boldsymbol{\epsilon}$$

$$\mathbf{x}_t \rightarrow max(\mathbf{x}_t, 0). \qquad (10)$$

Each element of $\mathbf{x}_t$ corresponds to an element in $\mathbf{c}_i^{\mathbf{IN}}$. τ is a time constant and κ is a leak parameter decreasing each item by its own strength. λ is a parameter that controls lateral inhibition, by scaling the strength of an inhibitory matrix $\mathbf{N}$ which connects each accumulator to all of the others except itself. $\boldsymbol{\epsilon}$ represents randomly distributed noise with mean 0 and standard deviation with model parameter η.

The process in Equation 7 runs iteratively until one of the accumulating elements crosses a threshold or until the recall period is over, determined by a fixed number of time steps in t. This equation is updated until one of the accumulating elements surpasses a threshold (here, set to 1), or until the number of time steps exceeds the amount of recall time that the model is allotted for the recall period. If an element surpasses the threshold, its corresponding item is recalled. The item is re-presented to the model, updating context according to Equation 2. Whereas the drift rate for temporal context varies between encoding and recall

(β^{temp}_{enc} and β^{temp}_{rec}, respectively) for simplicity the drift rate of the emotional context region is held constant between encoding and recall (i.e. ($\beta^{emot}_{enc} = \beta^{emot}_{rec}$). Once context is updated, this activates a different set of features on $\mathbf{f}^{\mathbf{IN}}_r$, and time permitting, the recall process in Equation 10 begins again.

Below we discuss two variants of eCMR, the category-only variant, and the attention-category variant. In the latter, one additional parameter (ϕ_{emot}) was used to model the effect of emotion on attention through an increase in the strength of association between the item features and the source context (M^{CF}). The association strength was increased via ϕ_{emot} such that experimental context-feature associations were updated:

$$\Delta M^{CF} = \phi_i \begin{bmatrix} L^{CF}_{tw} & 0 \\ \phi_{emot} L^{CF}_{sw} & 0 \end{bmatrix} \mathbf{f}_i \mathbf{c}_i{}^{\mathrm{T}} \tag{11}$$

Note that Equation 11 are identical to Equation 4 if ϕ_{emot} = 1, and requires ϕ_{emot} > 1 in order for emotional items to benefit from stronger associations and thus improved recall.

2.3 Simulations of the emotional list composition effect

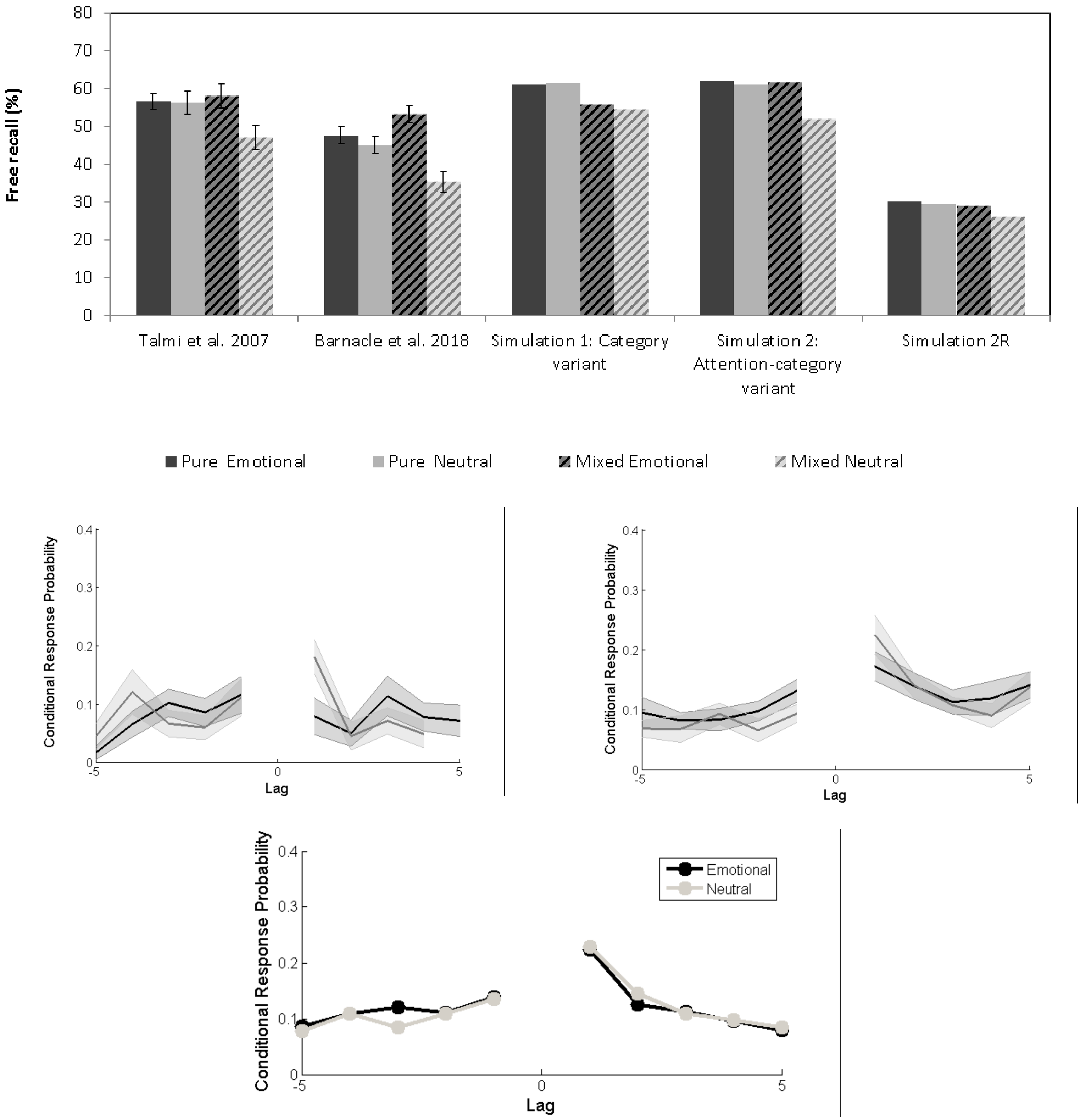


Figure 3. Recall data from Talmi et al., 2007, Experiment 2 (left) and the results of Simulations 1-2.

Top. *Average recall data. The attention-category (Simulation 2) variant of eCMR captured the emotional list composition effect, where emotion enhances memory in mixed but not pure lists. The category variant (Simulation 1) failed to do so. Error bars refer to the standard error of the mean.*

Middle. *Contiguity effects in the recall of pure lists in Talmi et al. (2007) and Barnacle et al. (2018). Black: emotional lists. Grey: neutral lists. The shaded thickness represents standard error.*

Bottom *Predicted contiguity effects in the attention-category variant of eCMR (Simulation 2).*

2.3.1 Simulation 1 - the category-only variant of eCMR

We first examined simulations of the *category-only variant* of eCMR, which treats emotionality as a category such that neutral items belong to a single category and emotional items belong to another, separate category, but emotional items are not otherwise treated specially. This variant of eCMR assumes, following the assumptions of CMR, that a change in a non-temporal context sub-region (here, a change between neutral and negative emotional contexts) disrupts the temporal context. In this way, temporal context is updated and all items studied prior to the novel item become less accessible. Thus, when two successive items are not from the same emotion category, temporal context is updated according to Equation 2. This "disruption item" only updates the temporal context sub-region, is not incorporated into the association matrices, and unlike list items, it cannot be recalled. Given that a change in emotional category is qualitatively different than a presented list item, it updates temporal context according to a different model parameter, d, rather than β (Polyn et al., 2009). Whereas in Polyn and colleagues' study the change in source context was a change in the orienting task, which required a change in the semantic operations performed on the presented stimulus, here the change in source context reflected a change in emotional category of the item, but otherwise the stimulus remained unchanged. Accordingly, we set the value of the disruption parameter d to a lower value than that used by Polyn and colleagues (**TABLE 1**). As mentioned in section 2.2, temporal organisation effects in Talmi et al.'s experiment were not pronounced. In order to align model predictions of temporal contiguity with those of the empirical data, we decreased the value of β_{enc}^{temp}, and decreased the weight the model assigns to temporal, compared to semantic, associations by decreasing $\boldsymbol{L_{tw}^{CF}}$. Because each section concerns different empirical results, obtained with lists that varied in their cohesiveness, we vary the value of $\boldsymbol{L_{tw}^{CF}}$ between sections (it was fixed within sections). Other than that we only vary parameter values to expose the machinery of the model, and this is discussed explicitly. Notably, most parameter values were fixed across all of the simulations reported here (Tables 1-2). The strength of semantic associations among items from the same category was simulated as 20% stronger than the semantic associations across categories. This remained constant across all of the simulations in all sections.

Figure 3 shows that the *category-only* variant predicted decreased memory in the mixed lists compared to pure lists. This decrease was due to the frequent disruptions to the temporal context during the encoding of mixed lists, which decreased the strength of associations between items, and the degree to which items were able to promote each other's recall. In contrast to the empirical results, though, the shared emotional context of emotional items did not benefit their recall over that of neutral items. This is to be expected because nothing in the model treated the emotional category differently from the neutral category: both emotional and neutral items could promote recall of items from the same category which shared their source context, be it emotional or neutral. The *category variant* cannot account for the recall advantage attributed to emotional items, as they are treated simply as a different category of item from neutral items. The next model variant addresses this simplifying assumption, by assuming that emotional items, in addition to being from a different source context from neutral items, also benefit from greater attentional processes during encoding.

2.3.2 Simulation 2 - the attention-category variant of eCMR

Given that the *category variant* failed to account for the list composition effect in Simulation 1, emotional items were further assumed to modulate attention, drawing on the consensus in the empirical literature. In CMR, additional attention to a subset of items - the earliest items in the list – is implemented by increasing the strength of association between item features to temporal and source contexts (equation 5). In this way, CMR assumes that primacy items draw attention to both experimental contexts of the presented items, i.e., temporal and source contexts. Although emotional items might also benefit from enhanced attention in the same way, the emotional items might only draw attention to their distinctive emotional (source) context, and not their associated temporal contexts. In the CMR framework, we can distinguish between these possibilities, by asking whether emotional items modulate item features to temporal context and/or item features to source context. Because increased association to the temporal context should be manifested as increased temporal clustering scores in recalling emotional, compared to neutral lists, and there was no evidence for this in the empirical data (section 2.1), increased attention to emotional items was implemented here as increased associations between emotional items and their emotional source context. One additional parameter (ϕ_{emot}) was used to model this effect of emotion (section 2.2, equation 11).

This variant of the model simulates an equivalent increase in attention to emotional and neutral stimuli in both mixed and pure lists. Because emotionality was modelled with a binary code all emotional items in pure lists were modelled as equally attended and none should draw more attention than another. In reality, of course, some items will be more emotional to participants than others, attract more attention, and would be more likely to win the competition for retrieval during free recall.

Figure 3 shows that, crucially, Simulation 2 yielded an emotional list-composition effect. The comparison between simulations 1 and 2 demonstrates that preferential attention to emotional stimuli, which increases contextual binding, is necessary to the model's ability to simulate this effect. The simulation predicted a recall advantage for emotional items over neutral ones in mixed, but not pure lists, despite equivalent attention advantage for emotional items in both types of lists. This result clarifies that differential attention alone is not sufficient to explain the decrease in memory for neutral stimuli in mixed lists. Instead, encoding and retrieval mechanisms interplay here such that the attention-dependent advantage of emotional items is more evident under conditions of competitive retrieval (in mixed lists). Section 2.4 unpacks the dynamics of retrieval to show how competition at retrieval works to favour emotional items in mixed lists. It shows that eCMR captures the above-chance temporal and emotional clustering scores observed in the empirical data.

2.4 The contribution of retrieval competition to the emotional list-composition effect

In this section, we unpack the retrieval mechanism of the *attention-category* variant of eCMR, which captured the emotional list composition effect. We begin by showing that this model, but not the *category variant*, predicts an earlier output of emotional compared to neutral items throughout the recall of mixed lists, because of their stronger connection to the source context of the test (2.4.1). This pattern agrees with the empirical data. Simulation 2R shows that this early advantage is a result of differential encoding of emotional items, even without further contributions from retrieval mechanisms (2.4.2). Simulations 2E and 2R explore the role of test context bias (2.4.3). They show that such bias does contribute to the advantage of emotional items, especially early on in the recall period, but that emotional items are recalled more frequently even when this bias is eliminated. This simulation therefore serves to reveal the contribution of retrieval dynamics to emotionally-enhanced memory in the model.

Early advantage influences retrieval by producing output interference. It changes the context of recall to be more emotional, and thus promotes recall of additional emotional items, and decreases the similarity between the temporal contexts of encoding and retrieval for neutral items. We present results from a new experiment to show that output interference cannot, on its own, account for enhanced recall of emotional items in mixed lists (2.4.4). To reveal how the competition between emotional and less-competitive (neutral) items during recall gives rise to enhanced emotional memory we analyse transitions during the recall, comparing predicted and empirical transitions (2.4.5). This analysis demonstrates that several dimensions of similarity multiply determine the emotion memory advantage in mixed lists.

2.4.1 Output order effects during recall of mixed lists.

In eCMR emotional stimuli are more strongly connected to the encoding context, which they all also share. This should give them an advantage at the first recalled position and throughout the early portion of the recall period. When an emotional item is recalled it should promote the recall of items similar to it - a selfperpetuating effect. Because emotional items share their emotional context they should promote each other's recall. For these reasons we should expect that emotional items will be recalled earlier than neutral ones. We examine the predictions from the two variants of eCMR for recall output and found that only the *attention-category* variant predicted an earlier output of emotional items in mixed lists (Figure 4). This prediction agrees with other empirical data depicted in Figure 4 and those of Siddiqui and Unsworth (2011). In summary, the analysis of empirical and simulated output order showed that emotional items are recalled earlier than neutral ones, confirming the prediction of eCMR. In the following sections, we explore other aspects of the retrieval that add to the memory advantage of emotional items in mixed lists.

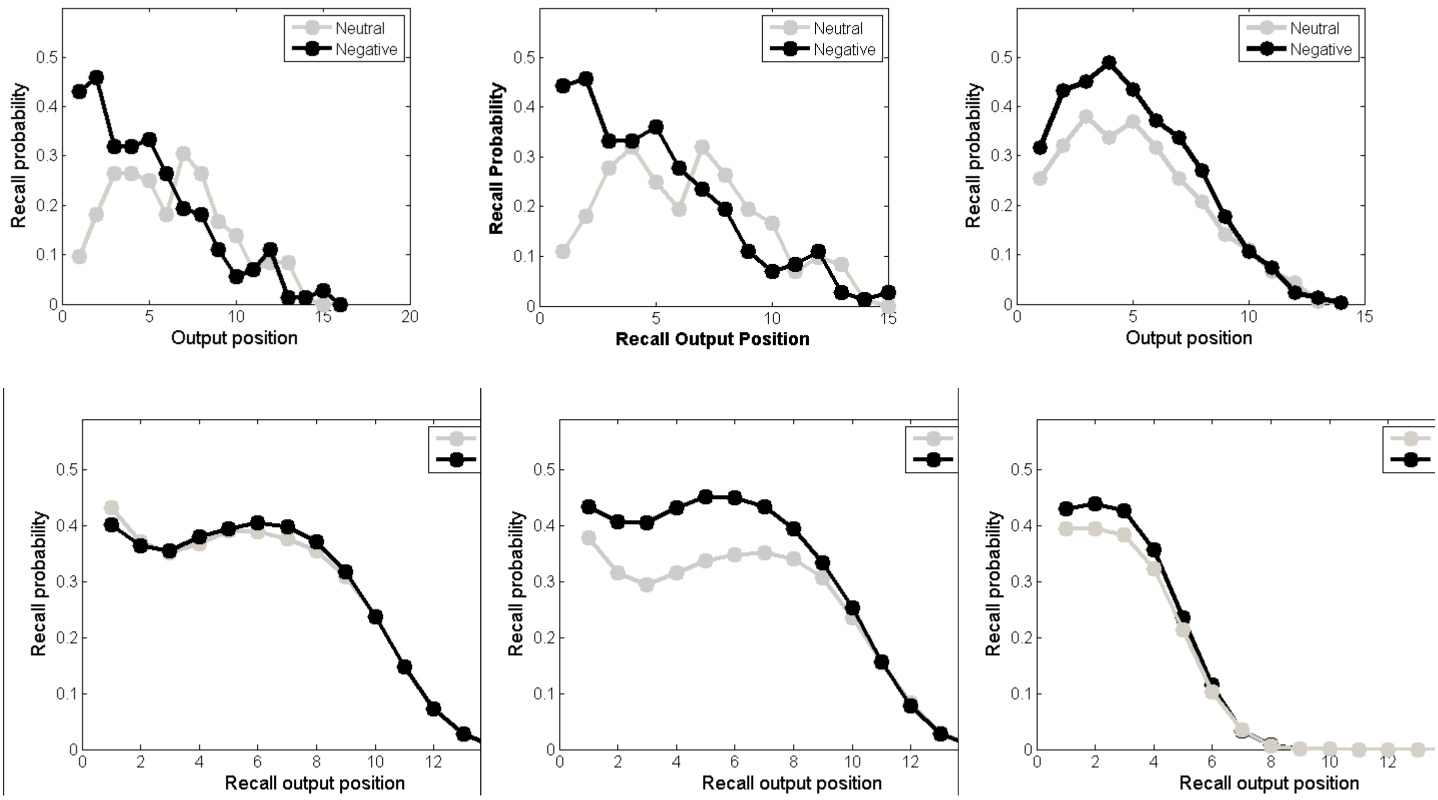


Figure 4. Earlier output of emotional items than neutral items in the recall of mixed lists.

Top. *Empirical output order effect. The probability of recalling items from each emotional category is plotted as a function of recall position, starting with the very first item recalled (simulation number in parenthesis). If all of the items recalled in the first recall position were emotional, the free recall probability of emotional items would* *be 1 and the probability of recalling neutral items would be 0.* ***Left:*** *Talmi et al., 2007, experiment 2.* ***Middle****. Output order effects in the experiment reported in Appendix 2.* ***Right.*** *Output order effects in Barnacle et al. (2018) data.*

Bottom. *Simulated output order for the category-only model (Simulation 1,* ***Left****), the attention-category model (Simulation 2,* ***Middle****), and a variant of the attention-category model where items cannot retrieve their encoding context (Simulation 2E,* ***Right****).*

2.4.2 Simulation 2R: Recall of mixed lists without retrieving the encoding context

Because emotional items are more strongly associated with the temporal context of the test, they should already have an advantage when recall commences, in the first output position. This advantage will influence the remainder of the recall period, even without any further influence of other aspects of the retrieval machinery of eCMR. To see this, Simulation 2R used all the same parameter values as Simulation 2, but eliminated the ability of recalled items to retrieve their study context by setting the parameters that update context during recall, $\beta_{rec}^{temp} = \beta_{rec}^{emot} = 0$. This simulation reveals, therefore, how stronger binding to the source context translates to early recall advantage. Overall recall in Simulation 2R was expected to be poorer, because the ability of each recalled item to retrieve its encoding context is a core aspect of retrieved context models, so eliminating it was expected to impair memory substantially.

Error! Reference source not found. plots the probability of recall in Simulation 2R as a function of output order, together with the results from Simulations 1 and 2, which were discussed above. It shows that, as expected the very first recall was not affected; it only depends on the initial test context, so should not be affected by the model's ability to retrieve the encoding context. It shows that emotional items have an advantage in the first recall position, and that even without any further contributions from retrieved encoding context, this advantage extended to output positions 2 and 3. This dovetails with the predicted average recall data, depicted in ***Figure 3***, where a small emotional list composition effect can clearly be detected. In summary, this simulation reveals that preferential encoding produces an advantage for emotional items in mixed lists; comparing simulations 2 and 2R reveals how the retrieval machinery in eCMR enhances this advantage.

*2.4.3 T*he contribution of retrieval dynamics to emotionally-enhanced memory

The early context of the test is influenced by the last items participants saw. If the source context is more emotional than it is neutral, it would favour retrieval of emotional items, and vice versa. But because emotional items are more strongly bound to the context, an emotional context bias during the test will exert a greater influence on recall than a neutral bias. Here we explore how context bias influences the advantage of emotional items in mixed lists.

We simulated an emotional or a neutral retrieval 'state' by including a distractor item at the beginning of the recall period. Distractor items update the temporal context but not the association matrices, and thus are not, themselves, candidates for recall (Sederberg et al., 2008; Siegel & Kahana, 2014). Here we interpolated distractor item with a null (Simulation 2O), emotional (Simulation 2E), or neutral (Simulation 2N) context just before the recall period. The magnitude of influence of this distractor item was controlled by β_{emot}. Only the mixed list condition was simulated.

In Simulation 2O we can see a small advantage for emotional items. Biasing the retrieval context with an emotional distractor – essentially, rendering it more emotional - increased the likelihood of recalling emotional items. Biasing the test context away from emotionality with a neutral distractor reversed the bias, resulting in increased first recall of neutral items. Crucially, because each recalled item retrieves its own source context, which dilutes the impact of the bias, no bias was observed in the second output position, and the emotional bias reappeared in the third output position (***Figure 5***).

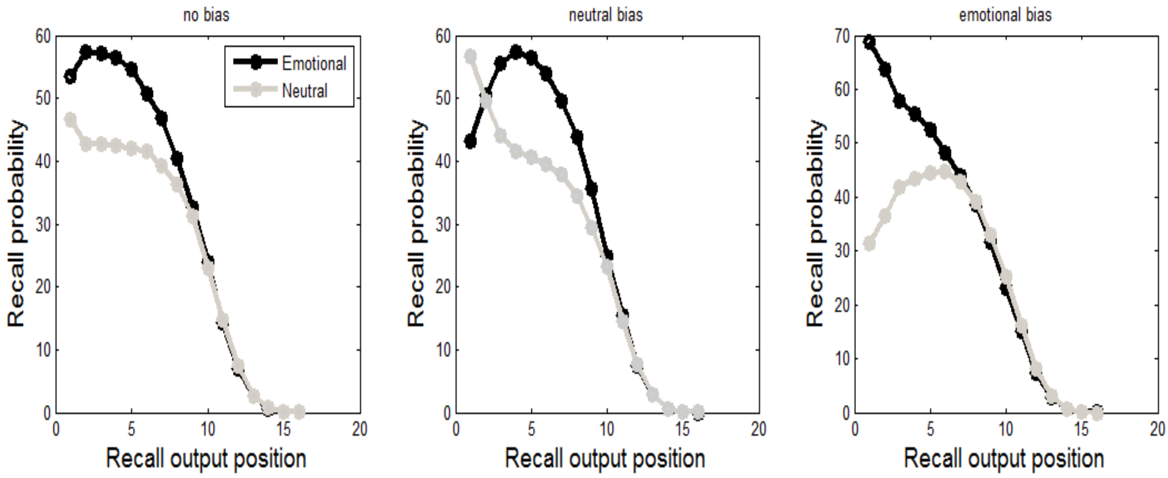


Figure 5. Free recall of emotional and neutral items, encoded in mixed lists, as a function of the emotional context of the test. Left. *No bias (Simulation 2O).* ***Middle.*** *Neutral bias (Simulation 2N).* ***Right.*** *Emotional bias (Simulation 2E).*

2.4.4 The emotional advantage in mixed lists does not depend solely on interference at retrieval

The earlier recall of emotional items could create output interference, which could produce the emotional memory advantage in mixed lists even without the other mechanisms postulated in eCMR. To examine the impact of output order on the emotional memory advantage in mixed lists we conducted a new experiment, described in **APPENDIX 1APPENDIX 2**. Retrieval of mixed lists of negatively-valenced emotional and neutral pictures was manipulated by asking participants to recall emotional or neutral items first (the 'emotional first' and 'neutral first' conditions). The crucial result for this section concerns the data from the 'emotional first' group, who were instructed to recall the emotional pictures first, and then the neutral pictures; and the 'neutral first' group, who were instructed to recall the neutral pictures first, and then the emotional pictures. Let us examine the predictions of eCMR for these conditions. An emotional memory advantage should still be obtained even when neutral items are recalled first, because emotional items compete for recall with items that are less strongly bound to the encoding context. While output interference is expected to decrease memory for both emotional and neutral stimuli, eCMR predicts that an emotional advantage should be present both when we compare the first recalls of each group (the recall of emotional items in the 'emotional first' group and the recall of neutral items in the 'neutral first' group), and when we compare the second recall of the two groups (the recall of neutral items in the 'emotional first' group and the recall of emotional items in the 'neutral first' group). By contrast, a greater difference in emotional versus emotional stimuli when comparing the first recall test to the second will support the hypothesis that this advantage depends on output interference. If the emotional memory advantage depends solely on output interference, then the emotional advantage should be greatly weakened in the first recall of the 'emotional first' and 'neutral first' groups, where such suppression is prevented, compared to the second recall of those groups, which more closely mimics the 'natural' uninstructed condition. The logic of eCMR dictates, however, that because emotional items are more strongly associated to the encoding context and to each other, the emotional advantage in mixed lists would remain even when output interference is reduced or eliminated – as long as emotional items compete for recall with non-emotional items. In this section, we describe empirical evidence in support of this hypothesis.

We observed a significant emotional memory advantage of equivalent magnitude in the first and the second recall (***FIGURE 6. Figure 5***). The analysis of the instructed conditions used two independent sample t-tests to compare recall of emotional and neutral items across the 'emotion first' and 'neutral first' groups. The magnitude of the effect of emotion on memory was equivalent and large in the first recall test (comparing recall of emotional items in the 'emotion first' group to neutral items in the 'neutral first' group), $t(34)=2.34$, $p<.05$, Cohen's $d=0.80$, and in the second recall test, (comparing recall of neutral items in the 'emotion first' group to recall of emotional items in the 'neutral first' group), $t(34)=2.20$, $p<.05$, Cohen's $d=0.76$. In summary, the effect size of the emotional memory advantage was large and roughly equivalent in both first and second recall, in accordance with the prediction of eCMR and going against the interpretation of the data as due solely to output interference.

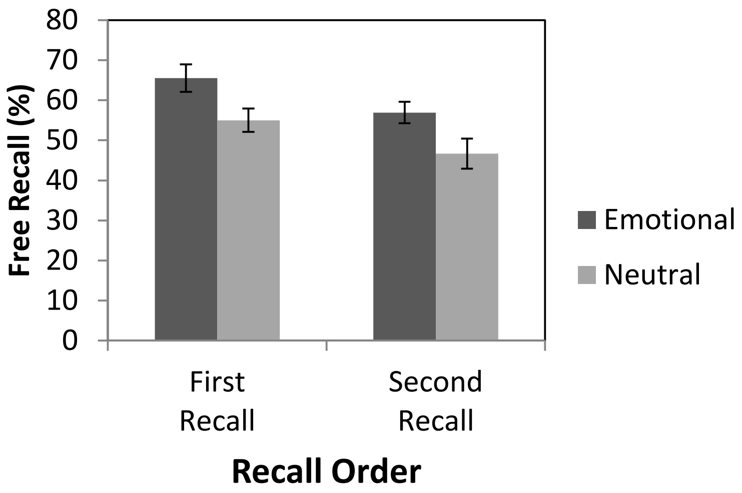


FIGURE 6. Empirical data from the instructed recall experiment (Appendix 2)

Free recall of the 'emotion first' and 'neutral first' groups is plotted as a function of the test period (the first or second recall). The two leftmost bars plot the recall from the first test period in each of these two groups (the emotional list in the 'emotion first' condition and the neutral list in the 'neutral first' condition). The two rightmost bars plot recall from the second test period in each of these groups (the neutral list in the 'emotion first' condition and the emotional list in the 'neutral first' condition).

2.4.5 Recall transitions in the attention-category variant of eCMR.

To fully understand the interaction between attention to emotion at encoding and the retrieval machinery of eCMR we analysed the types of transitions the model made between successive recalls in Simulation 2, following the same methodology used by Polyn and colleagues (2009, 2011), as described in section 2.1. The descriptive results are provided in **TABLE 4.**

Temporal clustering within category was greater than chance in the empirical data and in the model, reflecting both the shared emotional features, as well as the close temporal proximity, of these items. The model over-predicted between-category temporal clustering, reflecting the strong contribution of temporal associations between items even when they do not share the same emotional context. Next, we examined the emotional clustering scores. eCMR naturally predicts emotional clustering effect because recall of an item leads to retrieval of its associated context states, including its emotional context. Transitions based on shared emotional context in the model were more likely than what is expected at chance, as in the empirical data. We also saw a relationship, such that across simulated "subjects", recall probability of emotional items was greater when the emotional clustering score was high, while recall of neutral items correlated negatively with emotional clustering. This relationship was not observed in the empirical data, but as stated above, these data had limited power, and it is difficult therefore to interpret these null effects.

Lastly, we considered how transitions between successive recalls were influenced by semantic organisation. eCMR, like CMR, predicts that like temporal and emotional dimensions of similarity, semantic similarity should also contribute to recall. A semantic clustering score can be defined in a way analogous to the temporal clustering score, except rather than defining any pair's similarity based on their absolute temporal lag, similarity was defined based on the estimated semantic association in the simulation. The semantic clustering score in the model was greater than chance. We could not examine this in the empirical data because of the absence of an appropriate complete matrix of semantic similarity scores.

Taken together, these results show that in both the empirical data (section 2.1) and in Simulation 2, the dynamics of recall of mixed lists depend jointly on all of the associations that encoded items share. When an emotional item is recalled, it would most likely promote the recall of another emotional item. This is also true, of course, for neutral items; but because emotional items are recalled first, and promote recall of other emotional items via their shared emotional context that they are more strongly connected to, their recall benefits more from the propensity to cluster around the emotional dimension.

TABLE 4. Empirical and simulated recall transitions.

	Empirical data		Simulated recall
	Talmi et al. 2007	Barnacle et al. 2018	Simulation 2
Mixed lists			
Within-category temporal clustering	0.60* (0.19)	0.56* (0.10)	0.63
Across-category temporal clustering	0.50 (0.09)	0.51 (0.11)	0.64
Emotional clustering	0.67* (0.25)	0.59* (0.11)	0.59
Semantic clustering			0.56
Pure lists			
Emotional	.53 (.14)	.55 (.07)	.62
Neutral	.56 (.16)	55 (.11)	.62

Note. Means (SD) of temporal, source and semantic clustering scores. The asterisk denotes scores statistically greater than chance. For statistical tests see section 2.1.

2.5 Comparison of eCMR and the item-order account

eCMR formally embodies some of the same rationale of the item-order account, which was developed to explain non-emotional list composition effects for 'unusual' compared to standard items (McDaniel & Bugg, 2008). Like retrieved context models, the item-order account recognizes the central role of items' temporal order. Both the item-order account and eCMR assume that recall performance reflects a trade-off between the contributions of temporal context and other item characteristics. But the temporal order in the item-order account plays a different role than the temporal context in eCMR.

In the item-order account memory for the temporal order of list items helps recall only when it is attended during encoding. Attention to the temporal order is lower when more attention is allocated to processing the items' identity. In the item-order account, the balance between attention to the temporal order and the identity of items explains the list-composition effect (McDaniel and Bugg, 2008). Unusual items attract attention, so participants elaborate on their identity and pay less attention to their temporal order or the temporal order of any other list items. Therefore, attention to the temporal order of unusual items in pure lists is limited; it is greater when lists include some standard items (mixed lists); and greatest when there are no unusual items (pure lists of standard items). Recall of unusual items is unhurt regardless of list composition because the greater attention to their identity balances out the lesser attention to the temporal order. But when lists mix unusual and standard items the extra attention to the identity of unusual items comes at the expense not only of attention to their own temporal order, but also to the order of standard items, decreasing recall of standard items. In the item-order account attention to the temporal order helps recall by supporting forward recall transitions. Therefore, to support the item-order account, McDaniel and Bugg (2008) examined the "input-output correspondence index" (Asch & Ebenholtz, 1962), which is defined as the proportion of transitions made between successive items at lag=+1 (thus, the input and output order correspond to one another). In agreement with the predictions of the item-order account this index was lowest when participants encoded pure unusual lists, highest when participants encoded pure standard lists, and at a middling level when they encoded mixed lists (e.g. McDaniel, DeLosh, & Merritt, 2000). We computed the same index for the empirical datasets we simulated in this section, and found that the same was true for Talmi et al. (2007: pure emotional lists: M=.07, SD=.14; mixed lists: M=.10, SD=.09; pure neutral lists: M=0.14, SD=.13). In the Barnacle et al. dataset the input-output correspondence index was the same for pure emotional lists (M=.11, SD=.07) and mixed lists (M=.11, SD=.10), but, as predicted by the item-order account, higher for pure neutral lists (M=0.17, SD=.12). The difference between the input-output correspondence indices in the recall of pure lists was significant in both datasets. To make the links between eCMR and the item-order account explicit we computed the input-output correspondence indices for simulated data in Simulation 2, but did not observe much difference in the input-output correspondence index between list types (pure emotional lists: .15, mixed lists: .16, pure neutral lists: .16). The item-order account therefore predicts an aspect of the empirical data that eCMR does not. The parameters we selected for the simulations we reported in this section were based on the best-fit set in Polyn et al. (2009), so it is possible that a different selection of model parameters would allow eCMR to fit this result, but additional research with more powered empirical data is required to decide exactly what recall dynamics look like for the emotional list composition paradigm. eCMR did capture the above-chance temporal clustering scores in the empirical datasets, which collapse across all transitions, including the lag=+1 that the item-order account focuses on.

When we come to evaluate the two models in terms of their account of the list composition effect, perhaps the most important consideration is that the attention-category variant of eCMR can reproduce the list-composition effect without making the assumption that the item-order account makes - that attention to neutral items during the encoding of mixed lists is decreased, compared to the attention they receive in pure lists, and which contradicts the empirical data (Barnacle et al., 2016; Barnacle & Talmi, 2016; Talmi & McGarry, 2012). Unlike the item-order account, eCMR does not mandate a particular weighting of context dimensions. While reliance on the source context could decrease contiguity effects based on temporal context (Polyn et al., 2011, 2009), in the direction predicted by the item-order account, this did not happen in the empirical studies we reported here (TABLE 4). Overall, eCMR is a more comprehensive model, and can account for more aspects of the data than the item-order account; for example, only eCMR captured recall transitions based on source context, which were observed in the empirical data.

2.6 Summary

The empirical and simulation results in this section deconstruct the emotional memory advantage to its constituting elements. In both of the eCMR variants explored in section 2 emotional arousal was modelled as an emotional feature of items that updates an emotional context sub-region. An emotional (relative to a neutral) source context did not confer particular advantages. We equated the similarity of emotional and neutral items here (in keeping with the empirical work). In the *category* eCMR variant memory for both emotional and neutral items in mixed lists suffered from the disruption to the temporal context through the frequent alteration between item types. In the *attention-category* eCMR variant emotional items were modelled as systematically attended more, thus bound more strongly to their source (emotional) context and improving their chances of winning the competition for retrieval. This variant captured the pattern of average free recall and the dynamics of the emotional list-composition effect.

The success of eCMR to capture the emotional list composition effect depended on a number of retrieval mechanisms that interplayed with the additional attention towards emotional items during encoding. Overall, as in CMR, recall success in eCMR depended on the similarity between the retrieval context and the temporal, semantic, and (emotional) source context of encoded items. Emotional items in mixed lists were more likely to be recalled first because they were more strongly connected to the encoding context, and thus won the competition for recall. Once one emotional item was recalled, the shared emotional context between these items renders additional emotional items more accessible. We note that increased cohesiveness among emotional items, when this is not controlled experimentally, would also contribute in the same way. Because emotional items tend to be recalled early and promote each other's recall they act as a source of interference, making it more difficult for participants to retrieve neutral items. We showed that empirically, an emotional advantage is observed even when output interference is eliminated. The simulations clarified that an emotional advantage appears even when the initial source context of the test, and therefore the probability of first recall, was biased towards recall of neutral items.

In pure lists enhanced attention to emotional stimuli still increases their binding to emotional source context, but because the increased level of binding is equivalent for all of the emotional items, the competition for retrieval is affected by emotionality less than in mixed lists. Therefore, although encoding processes could be very similar in pure and mixed lists, the advantage of emotional items in free recall would be expressed more strongly in mixed lists. Taken together, there are several processes in place that give rise to the emotional advantage in free recall of mixed lists, rendering the emotional list-composition effect a robust phenomenon, well-described by eCMR.

3. eCMR accounts for increased emotion-enhanced memory after a prolonged delay

A paradigmatic finding in the emotional memory literature is that of a steeper forgetting of neutral compared to emotional stimuli (Yonelinas & Ritchey, 2015). In reports where the memory advantage is greater in a delayed test, the advantage may be smaller immediately and grow with delay (e.g. LaBar & Phelps, 1998); there may be no immediate advantage (e.g. Sharot & Yonelinas, 2008; Sharot & Phelps, 2004); or, in a few, classic, reports, emotional stimuli were remembered less well than neutral stimuli immediately, and the pattern reversed later (e.g. Butter, Training, & Kaplan, 1970; Kleinsmith & Kaplan, 1964). These studies used many different methodologies, which could well account for some of the discrepancies. But because the immediate effects are discrepant but the forgetting effects more consistent the consensus in the emotional memory literature is that attenuated forgetting has little to do with effects of emotion that can be manifested in immediate memory test, and, by extension, with encoding or retrieval mechanisms. Instead, the emphasis in the emotional memory literature has been the attenuated forgetting of emotional stimuli, and how this effect is implemented through neuromodulation (Dunsmoor, Murty, Davachi, & Phelps, 2015; Patil, Murty, Dunsmoor, Phelps, & Davachi, 2017).

Readers familiar with work on the neurobiology of memory consolidation may conclude, therefore, that eCMR has no hope of accommodating attenuated modulation of emotional items, because it lacks any mechanism to mimic consolidation effects. Although retrieved context models have been used to account for memory effects on time scales commonly used in human memory experiments – typically within the same day, model variants have been developed to explain consolidation-related effects, by assuming increased interference with time, or degraded context reinstatement (Howard, Kahana, & Wingfield, 2006; Sederberg, Gershman, Polyn, & Norman, 2011; Sederberg et al., 2008). In this section, we use eCMR to simulate a prolonged retention interval, and examine how delay might alter the emotional advantage. Our purpose was to illuminate which cognitive processes influence changes in the magnitude of the emotional memory advantage over time. eCMR is agnostic as to how such changes may be realised at the level of neurobiology.

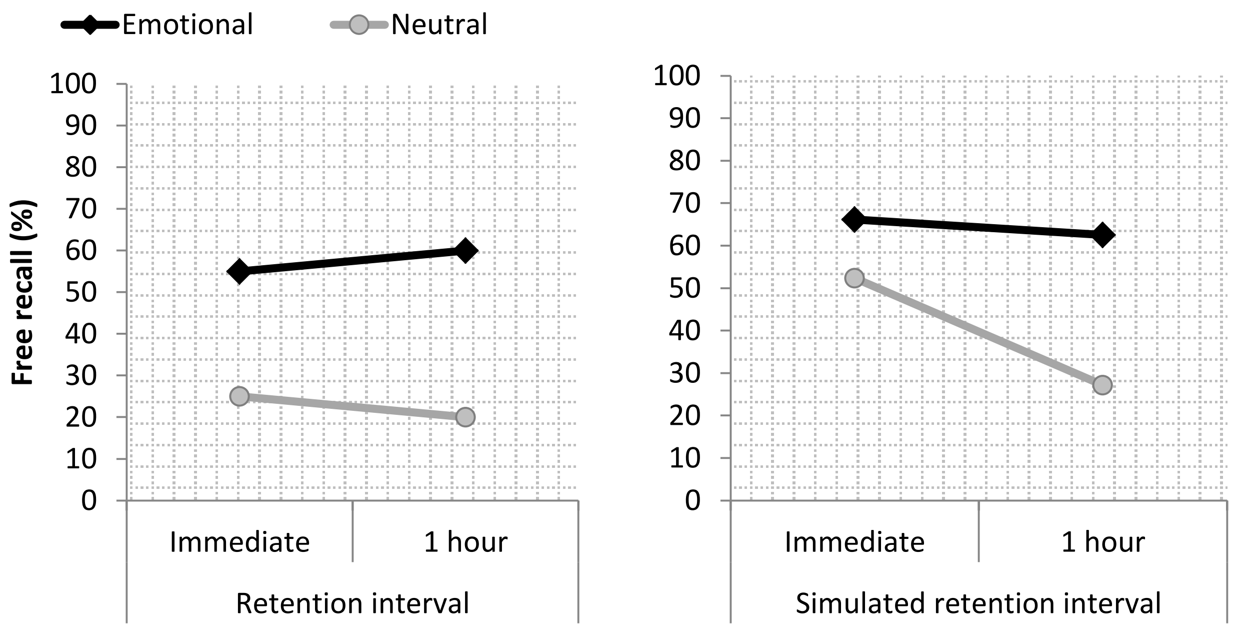
One way of simulating a retention interval is to simulate a 'distractor' item by inserting a temporal context disruption at the end of the encoding phase (Siegel & Kahana, 2014; Sederberg et al., 2008). While this approach has been successfully utilised to capture the effect of time delays in the order of seconds to minutes, it may not quite capture longer delays, such as the hours-to-weeks delays employed in the emotional memory literature. An additional problem with this approach is that in eCMR, once one item is recalled, this leads to retrieval of the item's encoding contexts and effectively allow the model to 'jump back in time', so that the effects of the retention interval would be limited to the first few recalls across retrieval attempts. Therefore, in addition to simulating post-list distraction, which does probably occur, we modelled the retention interval as decreasing the ability of a recalled item to retrieve its temporal context from encoding. To do this, we decreased the overall retrievability of the temporal context by decreasing β_{rec}^{temp}, an approach which has previously been employed successfully to capture the effects of aging on the recency and contiguity effects (Howard et al., 2006). In addition, we assumed that, after a delay, each item is less well associated with its own temporal context, so that it cannot retrieve it very well. For this purpose we decreased $\mathrm{L}_{\mathrm{wt}}^{\mathrm{FC}}$ and $\mathrm{L}_{\mathrm{tw}}^{\mathrm{CF}}$, an approach taken by Sederberg and colleagues to model part of the deficit in people with anterograde amnesia, which is characterised by poor delayed memory (Sederberg et al., 2008).

Because in eCMR all context dimensions support recall jointly, a decrease in the reliance of the model on the temporal context during retrieval, by necessity increase the reliance of the model on non-temporal dimensions such as the semantic and the emotional contexts. Therefore, the changes we implemented to simulate a prolonged retention interval correspond well to evidence that forgetting is not passive, but involves a transformation of memory traces so that memory for more remote events is more schematic (McKenzie & Eichenbaum, 2011; Moscovitch, Cabeza, Winocur, & Nadel, 2016). For example, animals that learned the location of a hidden platform in a Morris water maze based their trajectory more on the specific location of the platform when memory was recent, but were more sensitive to the probability distribution of platform locations when the memory was remote (Richards et al., 2014). A long retention interval is also thought to allow humans to extract generalities (Ellenbogen, Hu, Payne, Titone, & Walker, 2007) and render memory more schematic (Alba & Hasher, 1983). For example, remote memory for film clips relied more on general schemas for films and social scripts, evident in increased number of errors in recalling typical vs. atypical clips after a week (Bonasia et al., n.d.), suggesting increased relative accessibility of schema-relevant details after a delay (Sekeres et al., 2016). The literature does not, at present, specify exactly what time frame gives rise to more schematic memory performance. It is also possible that aspects of the experimental set-up, such as the stimulus set that is selected or the particular instructions participants receive, influence the strategies participants apply to the difficult task of delayed recall. Yet one prediction is clear: because non-temporal dimensions of similarity promote the recall of emotional items in eCMR, their greater influence after a delay is likely to increase in the simulated emotional advantage.

The most appropriate way to simulate memory delay is beyond the scope of this paper. Further research is needed to decide on the value of each of the parameters that might change with delay in a particular set-up. In order to examine the predictions of eCMR for delayed effects of emotion on memory we utilised a combination of the approaches implemented in retrieved context models elsewhere (e.g. Sederberg et al. 2008). Therefore, Simulation 3 could be seen as a proof of concept for greater effects of emotion in delayed tests, rather than a commitment for a particular implementation. To show this most clearly, Simulation 3 implements a classic experiment where emotional items had an increased free-recall advantage in a delayed, compared to an immediate test (LaBar & Phelps, 1998).

3.1 A description of empirical data from LaBar and Phelps, 1998

LaBar and Phelps (1998) studied healthy controls as well as patients with unilateral temporal lobectomy. Participants incidentally encoded a single mixed list of 20 low-frequency neutral words and 20 taboo words. Four buffer words were also included, two in the beginning and two at the end of the list. During encoding participants rated how arousing the words were. A free recall test was administered immediately and after a 1-hour filled delay. The researchers found an immediate increase in the number of taboo words recalled, which they attributed to the increased inter-relatedness of these words compared to the neutral words. Strikingly, participants forgot fewer taboo words, so that their memory advantage was greater after one hour than it was immediately, an effect they attributed to the effect of arousal on consolidation (***FIGURE 6.***). Notably, although the results suggested an *increase* in emotional memory after a delay, in the empirical data the interaction between item type and time was significant, but not the simple effects. The impact of this work is due, in part, to the finding that the participants with temporal lobectomy forgot taboo and neutral words at the same rate, in agreement with the hypothesis that the attenuated forgetting of emotionally arousing material is driven by the amygdala (LaBar & Cabeza, 2006).



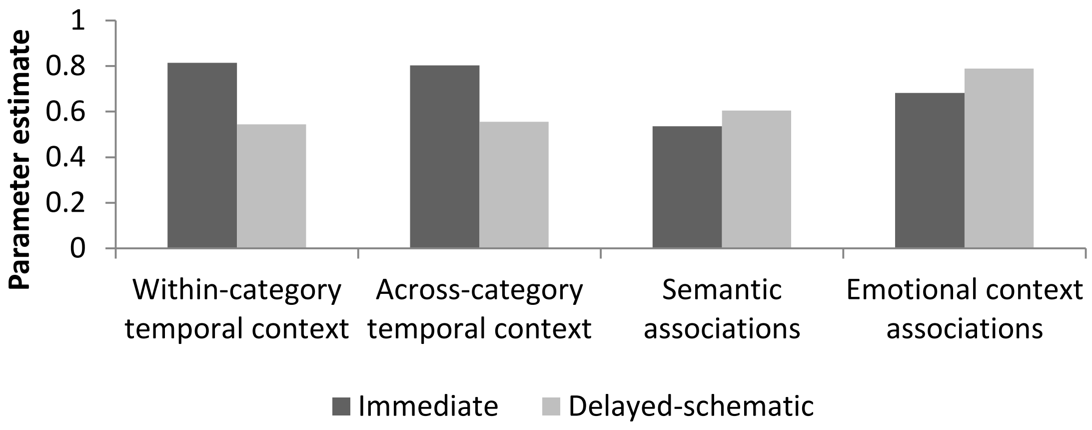


FIGURE 6. Forgetting effects.

***Top:** Emotional memory advantage as a function of time delay. **Left:** Original data adapted from Figure 2 in LaBar and Phelps (1998). Black: taboo words. Grey: neutral words. **Right.** Predictions of Simulations 3I and 3D.*

***Bottom.** Parameter estimates for predicted clustering effects in Simulation 3I and 3D.*

3.2 Simulations 3I and 3D: Immediate and delayed memory

We simulated 30 participants who each studied a list of 16 items, half of which were emotional. Note that we deliberately simulated lists that were shorter than those used by LaBar and Phelps (1998), in order to keep parameter estimates as close as possible to those used in section 2, and facilitate the comparison between the results in these two sections. Nevertheless, there were a few differences between Simulations 2 and 3. As in the original study the first and last two items were considered buffers and not analysed; two of these were emotional, two of these neutral, and they were allocated randomly to the 1st, 2nd, 17th and 18th list positions for every simulated participant. To better match the empirical setup of LaBar and Phelps, the simulated immediate test in Simulation 3I followed the encoding stage without simulating a distractor at the end of the list. Based on the discussion in the original paper, we assumed that emotional items were more inter-related to each other than the neutral items (the average semantic associations strength was 0.072 apart from among emotional items, where it was 0.09). Because LaBar and Phelps used neutral items which were not semantically related, it was likely that the semantic context played a less important role in immediate recall in their study, compared to the study we simulated in section 2. We therefore used the original value for L_{tw}^{CF} from Polyn et al. (2008).

In Simulation 3D the memory delay test was modelled by (1) simulating a distractor at the end of the list (2) decreasing β_{rec}^{temp}, which governs the overall ability to retrieve the temporal context (3) decreasing parameters L_{tw}^{CF} and L_{wt}^{FC}, which control the associations between temporal context and temporal item features (**TABLE 1**). These changes weaken the associations between the item and its temporal context. Consequently, recalling one item will promote the recall of items that share its temporal associations to a lesser extent, instead promoting the recall of items that share its semantic and emotional context.

3.3 Comparison between Simulations 3I and 3D

Simulations 3I and 3D captured the full pattern of data described by LaBar and Phelps (1998). About half of the neutral items were forgotten after a simulated delay, while memory for emotional items persisted. Compared to the recall advantage of emotional items in Simulations 3I, in Simulation 3D the model recalled both numerically and proportionally more emotional than neutral items (***FIGURE 6.***). It is well known that forgetting can be quantified in at least two different ways – the decrease in the number or the proportion of retained (Wixted, 1990); here the effects are large, and stand regardless of how forgetting is quantified. Further examination of these results suggests that increasing the value of the distractor at the end of the list, or decreasing β_{rec}^{temp} further, decreased recall of both emotional and neutral items, while the value of L_{tw}^{CF} and L_{wt}^{FC} influenced the relative forgetting of these item types.

The difference between the predictions eCMR makes for immediate and delayed memory can be elucidated by analysing the predictions those simulations make for the organisation of recall (see section 2.4.5 for details of the analysis method). ***FIGURE 6. FIGURE 9*** shows that simulated delay resulted in decreased temporal clustering scores, and increased influence of emotional and semantic factors on recall. Increased reliance on the semantic context with delay is reminiscent of the empirical demonstration that semantic similarity interacts with the retention interval, such that the relatedness of the retrieval cue and the target item influenced delayed cued recall more than immediate cued recall (Schooler et al., 1997). Simulation 3D suggests that the same might be true for the emotional context.

Taken together, the simulations in this section suggest that the attenuated forgetting of emotional stimuli with time - or even the absence of any forgetting at all - may not be a direct consequence of the retention interval, but an indirect consequence of the effect of the retention interval on the balance between the contextual dimensions that aid retrieval of particular memories.

4. The emotional oddball effect

In Sections 2 and 3 we considered recall of mixed lists where the number of emotional versus neutral items was equivalent, and in section 2 also recall of pure lists that were comprised entirely of emotional items or entirely of neutral items. To fully characterize the interaction of emotion and memory in recall we should also examine what happens when lists have other ratios of emotional to neutral items. An obvious case is the emotional oddball effect, where lists are comprised solely of neutral items, with the exception of one emotional oddball. For example, in a classic paper (Ellis, Detterman, Runcie, McCarver, & Craig, 1971) participants studied lists of line drawings of everyday objects for free recall. The emotional oddball was a picture of a model from a 'sun tanning' magazine, presented in a middling serial position. The oddball was recalled extremely well, while memory for surrounding items suffered, compared to control lists without oddballs. This decreased memory for items presented before and after the oddball is often referred to as retrograde and anterograde amnesia, respectively. Together with excellent memory for the emotional oddball itself, this pattern is referred to as the emotional oddball effect. The emotional list composition and the emotional oddball effects resemble each other because they are observed in tasks where emotional and neutral stimuli are presented in the same list and involve neutral memory impairments, as well as because both are sensitive to multiple cognitive processes (Schmidt & Schmidt, 2016).

Although the similarities between the emotional oddball effect and the emotional list composition effect suggest that eCMR should be able to predict both, the emotional oddball effect nevertheless presents a significant challenge to the model. The most obvious problem is that by definition, an oddball is less similar to standard list items compared to the similarity among standard items. In retrieved context models such as eCMR decreased similarity – however represented - would impair recall, contradicting the robust finding, known since the experiments of von Restorff, that deviant items are recalled extremely well (reviewed in Hunt & McDaniel, 1993). There are also plenty of demonstrations that this is true for an emotional oddball (Ellis et al., 1971; Hurlemann et al., 2005, 2007; Mather & Knight, 2009; Schmidt, 2012; Strange, Hurlemann, & Dolan, 2003).

This is not the only problem. In retrieved context theory, when an item is recalled it promotes the recall of items with shared context elements, including shared temporal context. This is a core aspect of the theory, and helps it explain temporal contiguity effects in free recall (Howard & Kahana, 1999, 2002a). If eCMR could simulate the excellent recall of the oddball item, then its recall will promote the recall of those items presented before and after it (oddball-1 and oddball+1). Yet this prediction is exactly the opposite of the retrograde and anterograde amnesia aspects of the empirical oddball effect, which is thought to be even more accentuated when the oddballs are emotional (Hurlemann et al., 2005, 2007; Mather & Knight, 2009; Strange et al., 2003). Admittedly, the exact pattern of oddball-induced retrograde and anterograde amnesia vary; there have been reports of retrograde without anterograde amnesia (Tulving & Thomson, 1973), anterograde without retrograde amnesia (Schmidt, 2002), or both anterograde and retrograde amnesia (Detterman & Ellis, 1972). But Schmidt and Schmidt (2016) review the literature on the emotional oddball, and conclude that amnesia effects in tasks such as immediate free recall are robust. Specifically, they suggest that anterograde amnesia effects are robust across stimulus types and types of test (recall and recognition), and that retrograde amnesia effects are observed consistently in recall tests that take place shortly after encoding, as in the cases we simulate here.

In eCMR we have a ready mechanism to implement increased attention, which could go some way to counteract the dissimilarity of the oddball to the context, and boost its recall. Yet boosting the recall of the oddball is unlikely to address the problem of anterograde and retrograde amnesia for items near the oddball. One possible resolution to this discrepancy between the emotional oddball effect and the generic predictions of retrieved-context theory has to do with the assumption of CMR that the temporal context is disrupted whenever item sources change, something that occurs when an emotional item is presented after a series of neutral items, or vice versa. We examine these solutions below. Our main aim in this section is to see what mechanisms in eCMR are sufficient to predict the superior memory for an outstanding isolate, and examine which of these also impair memory for items in close serial positions. By examining what elements of eCMR need to change in order to reproduce the emotional oddball effect we may develop deeper understanding of the empirical effect.

4.1 Simulation 5: Representing an oddball in eCMR

By definition, an oddball is an item that is *different* from the standard list items. The attention-category variant of eCMR already has the means to represent this difference. An oddball may trigger different internal operations than the standards. This can be readily operationalised in eCMR through oddball and standards having different source contexts. Notably, so far we have only considered source contexts that are emotional and neutral, but the same approach can be used to represent other differences in the encoding of standards and oddballs, such as the difference between standard words and an oddball picture, for example. Because the test context will be dominated by the source context of the standards, an oddball with a different source context should be recalled less well. Additionally, an oddball may also be less related to standard items on a certain dimension, such as its pre-experimental semantic associations. This is certainly the case for mixed lists of emotional and neutral items, where even if these two item categories are equally cohesive, they are less related to each other. Again, because the list context will favour items that are semantically similar to the standards, decreased similarity will hinder the recall of oddballs. Increased attention to the oddball may counteract these effects. Emotional oddballs would attract attention both because they are emotional and because they are unexpected; unexpected items are attended and processed preferentially (Kok, Rahnev, Jehee, Lau, & de Lange, 2012).

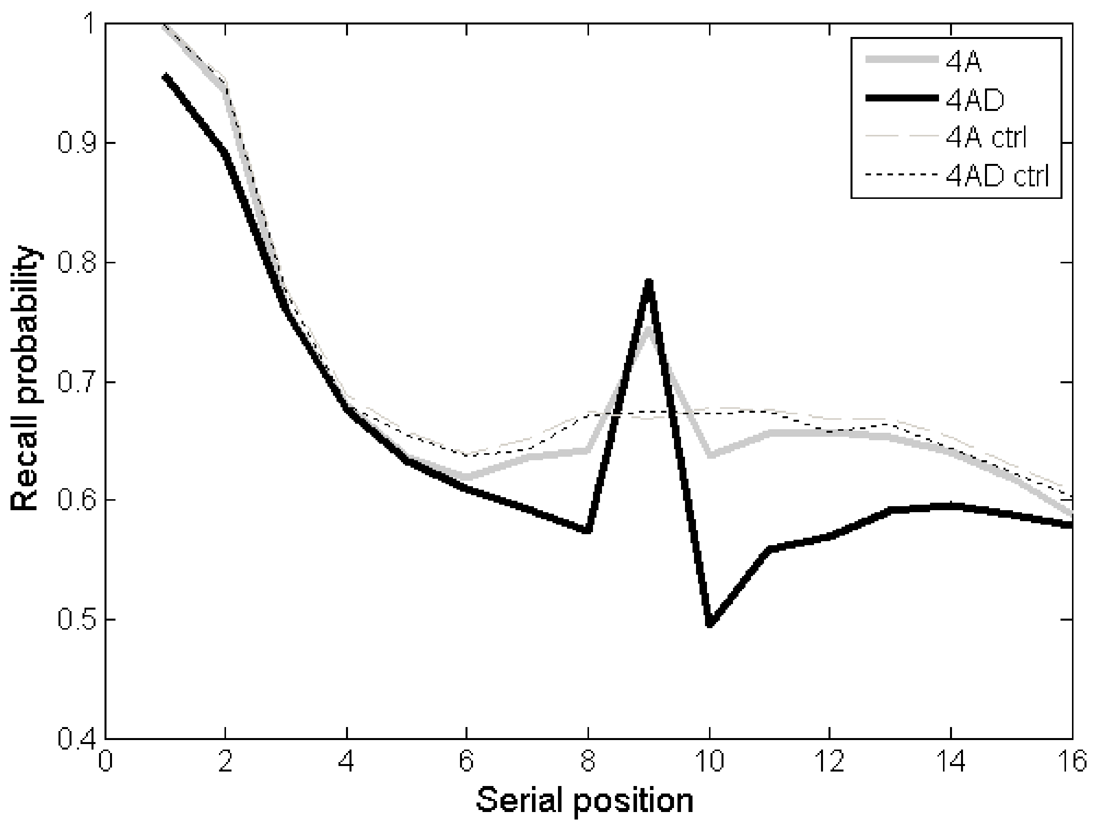
Taken together, the balance between preferential attention, different source and weaker relatedness would determine how well an oddball is remembered. While an oddball can be represented very much like emotional items were represented in the attention-category variant of eCMR, the balance between these influences - how much an oddball disrupts the temporal context, how much less related it is, and how much attention it attracts – may be different.

In Simulation 5 we simulated lists of 16 items, 15 of which were neutral, with a single emotional item in position 9. The same list length was used in Simulation 2; this list structure is similar to the one used by Ellis, Detterman and colleagues (Ellis et al., 1971). We also simulated control lists, which included 16 neutral items. Simulation 5 used the attention-category variant of eCMR and the same parameter values, apart from the degree of reliance on the semantic associations, which was higher compared to Simulation 2, where we simulated cohesive lists, but lower than the value used for Simulation 3, where we simulated randomly-selected lists. This simulation did not predict superior memory for the oddball compared to standards, but the reverse, a dip in memory for the oddball (***TABLE 5***). It is useful to consider this prediction, because it exposes the challenge that the emotional oddball effect poses for eCMR.

In Simulation 4A we shifted the balance between the various mechanisms that implement the oddball by simulating an oddball that attracts more attention than emotional items in mixed lists. Simulation 4A captured the idealised pattern we described as the emotional oddball effect: excellent memory for the oddball itself, accompanied by worse memory for items in other list positions, compared to control lists without oddballs (***FIGURE 8***)***FIGURE 9***. Memory for items near the oddball was particularly impaired, a result that amounts to anterograde and retrograde amnesia effects for items near the oddball. In the next section we turn to empirical data, to reveal how the mechanisms we used to simulate the oddball in Simulation 4A is likely to be specific to emotional oddballs.

TABLE 5. Recall (%) in Simulation 5.

	Oddball list	***Control list***
Positions 1-8	76.22	75.30
Oddball (position 9)	29.24	66.10
Positions 10-16	63.46	64.66



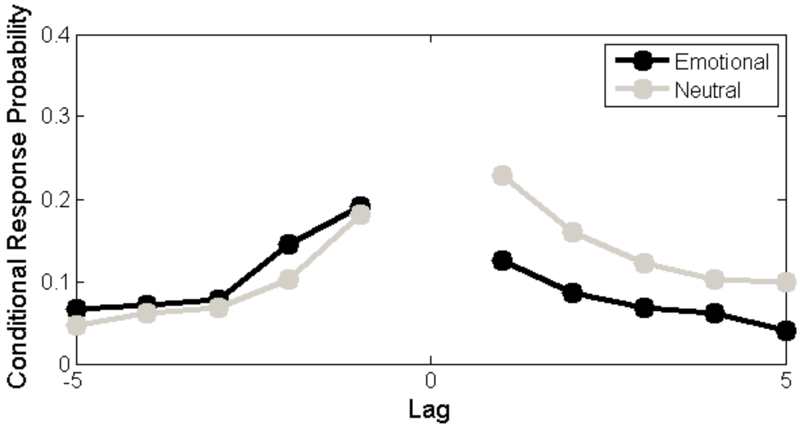


FIGURE 8. The emotional oddball effect.

Top. *Predicted recall in Simulation 4A and 4AD for lists that included a single oddball item in position 9 and for control lists comprised of standard items only, as a function of serial position. Simulations 4A and 4AD differed in the degree to which the oddball disrupted the temporal context. Predicted recall in this latter pair of simulation matched the empirical pattern (see* ***FIGURE 9****), if we consider 4A to simulate the neutral oddball and 4AD to simulate the emotional oddball.*

Bottom. *Predicted conditional recall probability as a function of lag, depicting transitions from the emotional (black) or neutral (grey) oddball. The plot shows decreased tendency to retrieve the item that follows the emotional oddball.*

*4.2 C*omparing emotional and neutral oddball effects: Simulations 4AA and 4AD

Unexpected neutral and emotional items have both been linked to a similar neurobiological mechanism involving temporo-parietal activity and the neurotransmitter noradrenalin (Mather, Clewett, Sakaki, & Harley, 2017; Polich, 2007). To decide which aspect of the emotional oddball effect is specific to emotional oddballs, compared to neutral ones, we refer to a set of empirical investigations of the emotional oddball, unique in that the same procedures were repeated across two laboratories in three different studies (Hurlemann et al., 2005, 2007; Mather & Knight, 2009). Participants in these studies encoded 9 pictures in each list: 8 pictures of everyday objects, and a single emotional or neutral oddball picture in the middle of the list, depicting people in emotional or neutral scenes (Knight and Mather 2009 mention some examples: standard items included pictures of a salad or a brush; neutral oddballs include pictures of people cooking or cleaning). A free recall test was administered after a short distractor task. The key findings were superior memory for oddballs, both emotional and neutral; and an impairment in memory for the items presented before the emotional oddball, compared to items presented before the neutral oddball. The results were consistent across these three experiments (***FIGURE 9***).

We have discussed the ways in which oddballs in eCMR are different from standards. Most of these differences influence memory for the oddball itself (having a different source, semantic relatedness, attention). The only aspect of the oddball representation in eCMR which is relevant to memory for nearby positions is the disruption to the temporal context occasioned by source context switches. The degree of disruption is controlled by parameter d. As discussed in section 1, CMR assumed that switching between source contexts disrupts the temporal context, making it more difficult to retrieve items that were presented near in time but have a different source context. This assumption was retained in eCMR, but so far we have assumed that it was not a strong disruption, as manifest in a low parameter value for d. Simulation 4AD considers a more pronounced disruption by increasing d. That temporal context disruption plays a larger role in emotional oddball lists compared to mixed lists is consistent with the intuition that a single oddball is more surprising to participants, and therefore results in more unique encoding operations that resemble a task-switch, compared to alternations that occur throughout the entire list, for example when half the list items are emotional and half are neutral. Assuming temporal context disruption around an emotional oddball does not mean that the source context is equally disrupted. Thus, we can assume that the emotional repercussions of viewing a picture of a nude model or a taboo word continue to colour the emotional context when simulated participants encoded the items that followed the oddball item.

The comparison between Simulation 4A and 4AD will help clarify the predictions of eCMR for a neutral and an emotional oddball that are equally attended, but where the emotional oddball disrupts the temporal context more than the neutral oddball. To best relate these simulations to the empirical pattern (***FIGURE 9***) we can think about Simulation 4A as a simulation of a neutral oddball; and Simulation 4AD as a simulation of an emotional oddball.

Memory for the oddball in Simulation 4AD (the emotional oddball) resembled memory for the oddball in Simulation 4A (the neutral oddball), but the emotional oddball caused a decrease in memory for nearby list items (***FIGURE 8***). This pair of simulations therefore captured the empirical findings (***FIGURE 9***), suggesting that the empirical difference between emotional and neutral oddballs (Hurlemann et al., 2005, 2007; Mather & Knight, 2009) has to do with the degree of disruption to the temporal context when the source context switches between emotional and neutral sources.

The temporal organisation of simulated recall suggested that neutral and emotional oddballs were recalled early, in agreement with the predictions the model made for the list composition task, and with empirical data (Elhalal, Davelaar, & Usher, 2014). In the control lists of Simulations 5A and 4AD the item in position 9 was recalled first around 5%-6% of the time. By contrast, the 'neutral' oddball in 4A was recalled first 21% of the time, and the 'emotional' oddball in 5E was recalled first 53% of the time. Finally, we examined which items the model tends to recall after it recalls the oddball (***FIGURE 8***). This analysis suggests that the disrupted temporal context around the emotional oddball decreased forward transitions to nearby items.

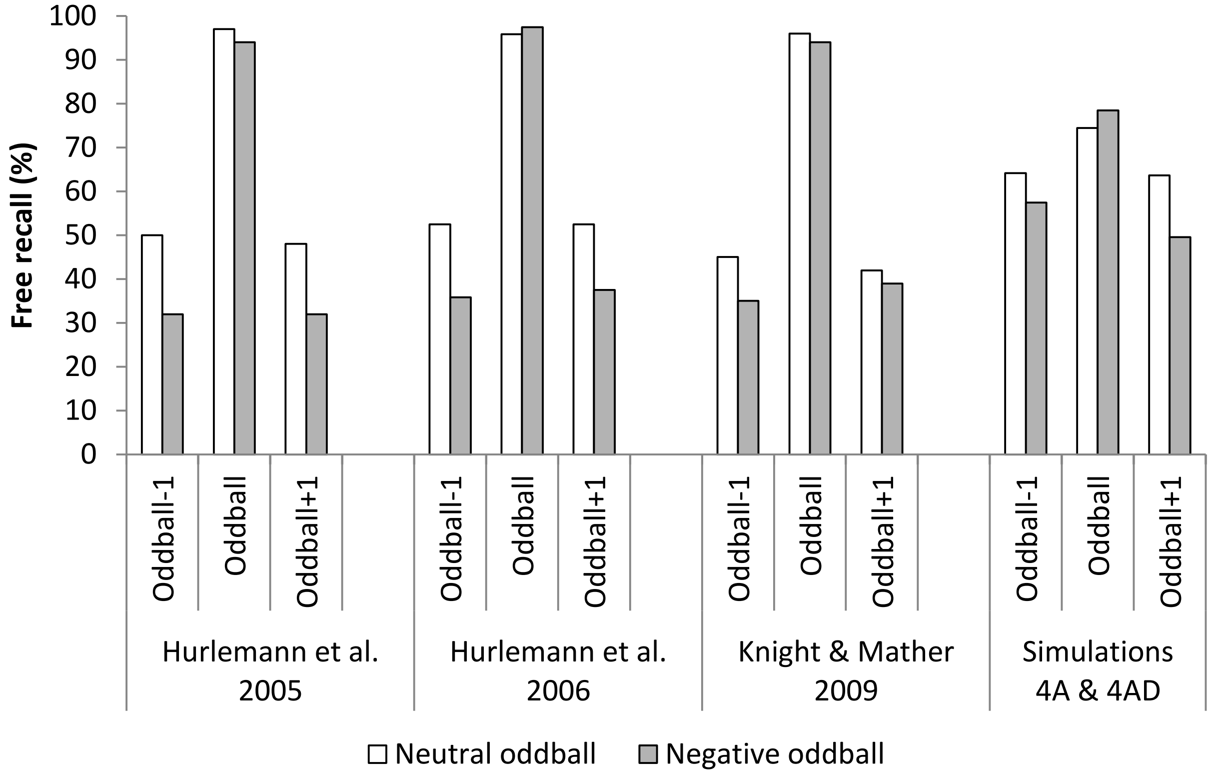


FIGURE 9. Empirical and simulated results depicting memory for an emotional and neutral oddball and surrounding items. *The simulated data refers to the predictions of Simulation 4A (for the neutral oddball) and 4AD (for the emotional oddball).*

4.3 Summary

In contrast to perfectly mixed lists with an equal number of neutral and emotional stimuli, here we consider lists which include a single emotional "oddball" item. It was important to consider the emotional oddball effect, because it appeared potentially challenging to eCMR. Indeed, we saw that with the parameter values used to simulate the list composition effect, we did not obtain an oddball effect. Our aim in this section was to show that eCMR can simulate this effect, and offer insights as to the factors that might allow it to do so. We focused on identifying the elements of the oddball effect that were specific to emotional, compared to neutral oddballs, because we had robust empirical data to compare to the simulated recall. eCMR provided a good qualitative fit to a set of results that have been replicated several times in different laboratories.

While more data would help constrain the selection of parameter values, the simulations conducted here provided novel predictions that can be tested empirically. First, eCMR could capture superior memory for oddballs compared to standards only when oddballs were simulated as attracting more attention than emotional items in mixed lists. To test this prediction future research could manipulate the proportion of emotional items in the list and measure attention empirically by using a divided attention task or EEG recordings (Barnacle et al., 2018; Pottage & Schaefer, 2012; Talmi, Schimmack, et al., 2007). Second, the degree of impairment to recall of items before and after the oddball in lists that included an oddball, and in control lists, was affected by the degree of disruption to the temporal context, not by increased attention to the oddball. The degree to which oddballs disrupt the temporal context can also be measured empirically using subjective time estimations (Block & Reed, 1978; Sahakyan & Smith, 2014).

5. Discussion

The work presented in this paper proposes a shift in the way we understand memory for important experiences, those that trigger emotional arousal. It is well-established that some experiences attract attention and are processed preferentially: those with certain features that our species has evolved to prioritise, those previously associated with reward or punishment, and those that appear to promote our current goals. It has previously been thought that the memory traces laid down during the encoding of emotionally-arousing experiences are maintained in a special way so that important events will have the best chance of influencing later fitness-related decisions. eCMR shows that the nature of the memory traces themselves – the increased binding between them and their encoding context, and their inherent associations to other emotionally arousing and semantically related memory traces – is sufficient to give them an advantage during test, which is amplified in delayed tests, when they compete for retrieval with neutral items. Differences that are already evident at encoding between emotional and neutral items protect and promote them whenever there is a competition for retrieval later on, and give rise to emotion-enhanced memory even without further post-encoding advantages. The dynamics of retrieval determine the magnitude of this advantage and could increase or decrease it. eCMR therefore highlights the exquisite sensitivity of memory to the situation in which an agent finds itself – in eCMR, the retrieval context of the memory test – by providing mechanisms which prioritise the retrieval of experiences that best match that test context across multiple dimensions of similarity.

eCMR is the first quantitative model of the emotional enhancement of memory. It explains the improvement in remembering emotionally arousing stimuli as arising from the operation and modulation of retrieved context mechanisms during encoding, maintenance and retrieval. Emotional arousal is operationalised in the model as a feature of items that is associated to their source context. We assumed, in agreement with the consensus in the literature (reviewed, for example, in Mather & Sutherland, 2011; Pourtois et al., 2013) and our own previous findings (Talmi & McGarry, 2012; Talmi, Schimmack, et al., 2007), that stimuli that trigger emotional arousal attract attention obligatorily. Building on previous work, extra attention was described in the model as the strengthening of associations between the attended item and its encoding context (Howard & Kahana, 2002a; Lohnas et al., 2015; Polyn et al., 2009). eCMR therefore is compatible with the suggestion that emotional stimuli are bound more strongly to their context (Hadley & MacKay, 2006; MacKay & Ahmetzanov, 2005; MacKay et al., 2004), although it specifies that the increased binding is with the sub-region of the encoding context that represented the items' source, which is emotional or neutral. Crucially, eCMR goes beyond previous work, revealing that emotion-enhanced memory is not solely a result of prioritised encoding, but is also the result of retrieval competition, extending to this situation the logic of CMR (Polyn et al., 2009) and its predecessors. The increased association strength between emotional stimuli and their source context, and the shared source context among emotional items, render emotional items more competitive during retrieval even when their semantic cohesiveness is equated with that of neutral stimuli. Therefore, when the model attempts to retrieve emotional and neutral items that were encoded together in mixed lists, the emotional ones are recalled early and promote each other's recall, which interferes with and delays the recall of neutral stimuli. When the memory test takes place after a prolonged interval, the model assumes that the temporal context is less diagnostic, so non-temporal context features such as shared emotional context and the oft-stronger semantic associations between emotionally arousing stimuli boost retrieval chances even more. But when emotional items compete against other highly-attended emotional items, the extra attention they receive at encoding does not help very much at retrieval, so that, recall of pure emotional lists is a lot closer to recall of pure neutral lists. In summary, eCMR uses the established mechanisms of retrieved context models to describe emotion-enhanced memory as a consequence the interplay between encoding, maintenance, and retrieval effects.

The data presented here support eCMR as a model of the effect of emotional arousal on immediate free recall. eCMR provided a good qualitative fit for the emotional list composition effect and the emotional oddball effect, phenomena related to differences between the average recall of emotional and neutral stimuli. In the recall of mixed lists the increased average strength of associations between emotional items and their context supported their enhanced recall, while in the recall of pure lists the increase in the strength of average associations between items and their context no longer mattered. In reality, what would matter for recall of pure lists would be the fluctuation in attention that individual participants may allocate to individual items. This realisation now provides an explanation to a finding we reported a few years back, when we used structural equation modelling to relate attention at encoding and free recall performance (Talmi & McGarry, 2012). Participants in that study encoded pure and mixed lists of emotional and neutral pictures under full or divided attention. Performance on the concurrent task worsened in terms of accuracy and reaction time when participants encoded emotional, compared to neutral pictures, regardless of list composition. We used performance on the concurrent task to compute an attention score for every picture (across participants), a measure which correlated with the arousal ratings each picture received. Intriguingly, we found that in free recall of mixed lists, arousal ratings predicted recall directly, an effect which was not mediated by attention; but in pure lists the effect of arousal on memory was completely mediated by attention. The current modelling explains these findings because a little more attention to particularly arousing pictures in a pure list can certainly boost retrieval success, but its impact will be drowned out in mixed lists when all emotional items are attended a lot more than all neutral items.

A list with one emotional oddball is also, in a way, a mixed list. eCMR captured the emotional oddball effect too, under the assumption that an oddball attracts more attention than an emotional item in a list with many other emotional items – an assumption that should be investigated empirically. Without that assumption the recall of oddballs was poorer than the recall of control items; but increased attention to the oddball resulted in good memory for it, as well as a decrease in memory for items in nearby positions. Empirical data suggested that only the latter was specific to emotional oddballs, compared to neutral oddballs. eCMR predicted that this only happens if an emotional oddball disrupts the temporal context more than a neutral oddball - a novel prediction. This prediction can be tested empirically through retrospective time estimations, which are sensitive to the number of different patterns that are encoded into episodic memory (Faber & Gennari, 2015) and are thought to index the magnitude of drift of temporal context (Block & Reed, 1978; Sahakyan & Smith, 2014). Recently, Johnson and MacKay (Johnson & Mackay, n.d.) obtained evidence that emotional oddballs disrupt the temporal context. They presented participants with a list of 6 words. One of the words was always a taboo word and the others were neutral. At the end of the list participants were asked to estimate the duration of the last word, which was either a taboo word or a neutral word. The duration of the taboo word was estimated to be longer than the duration of the neutral word. More direct evidence for the predictions of eCMR that emotional oddballs disrupt the temporal context more than neutral oddballs will require comparing the taboo word to a neutrally-valenced oddball word.

eCMR also captured well the dynamics of recall. The stronger association between emotional stimuli and their context in eCMR increases the chances that emotional items will win the retrieval competition early in recall, so the model predicted earlier recall of emotional stimuli studied in mixed lists and the earlier output of oddball stimuli. This prediction has also been confirmed empirically, as shown here for the list composition effect using a number of different datasets, and reported in the literature on the emotional oddball (). Emotional and semantic associations between emotional stimuli help them promote each other recall, and therefore the model predicted above-chance transitions based on the emotional context of stimuli. This prediction, too, was confirmed, both in previous data where clustering recall around the emotional category was observed (), and in new analysis of data from our archive. Biasing the model so that recall begins with a more neutral context prevents the model from recalling emotional items first, but they gained the upper hand very quickly. This occurs when neutral items are recalled they retrieve their context, which helps them promote the recall of items more strongly bound to that context – the emotional items. Emotional items then further promote the recall of items that share their emotional and semantic context. The prediction that emotional items will be recalled better than neutral ones even when the initial retrieval context is biased against them is in keeping with new data, from an experiment where participants encoded mixed lists, and then were instructed which item type to recall. More emotional items were recalled than neutral ones both in the first recall test *and* in the second recall test, where the instructions switched to the other item type. In summary, this investigation shows a multiply determined effect of emotion on retrieval dynamics, which together with enhanced attention at encoding gives rise to the robust emotional memory enhancement in immediate free recall of mixed lists.

Our simulations showed that eCMR predicts increased retrieval success when the context of encoding and test is similar. This occurred when memory for emotional (neutral) items that were encoded in mixed lists improved when the source context of the test was biased towards emotional (neutral) items. This is reminiscent of state-dependent memory effects – the established improvement of memory performance when participants are in the same 'state' at encoding and retrieval (Smith & Vela, 2001). States can physiological, e.g. when induced through psychopharmacological manipulations, or psychological, for example through mood inductions (Blaney, 1986; Bower, 1981; Ucros, 1989). eCMR predicts enhanced recall when the emotionality of the retrieval state matches the emotionality of the encoding context, suggesting that it may be able to capture state-dependent effects. Although here the dynamics of recall meant that their impact dwindled quickly, so the initial state had only a limited impact on average recall, it could have a larger impact in situations where the original context is less accessible.

5.1 Relating eCMR to other models

The model we developed here is useful because it can account for many emotional memory phenomena. Some of the effects the model describes, which have been discussed in previous work in terms of the contribution of emotional arousal, are here revealed as similar to non-emotional effects. The emotional list composition effect is, of course, reminiscent of list composition effects that arise from non-emotional manipulations of unusualness, such as bizarreness, enactment, generation, word frequency and perceptual interference (McDaniel & Bugg, 2008). The increased item-to-context associations, which in eCMR are discussed as a consequence of emotional arousal, may also be true for other neutral categories, such as enacted or generated items. Whether eCMR can account for non-emotional list-composition effects depends on whether additional attention is allocated to each one of the unusual stimuli, and on the semantic associations between all of the items. eCMR can perhaps be seen as an extension and quantification of the item-order account, where various item dimensions that receive attention at encoding can balance out memory impairment stemming from reduced attention to others. The emphasis on increased attention at encoding as a driver for the emotional memory enhancement in mixed lists distinguishes the emotional list composition effect – and other list composition effects for unusual items - from the list strength effect (Ratcliff et al., 1990), which is not obtained when items are rendered 'strong' through manipulations that resemble enhanced attention (either a longer encoding time or deeper elaboration, Malmberg & Shiffrin, 2005).

The success of eCMR in modelling the emotional list composition effect can be contrasted with the predictions we can extract from the Scale Invariant Memory and Perceptual Learning model (SIMPLE; Brown, Neath, & Chater, 2007). Neath and Brown (Neath & Brown, 2006) proposed that short words are easier to comprehend, which makes them more distinctive compared to long words. Through this insight they showed that SIMPLE captures the findings that memory for a pure list of short words is better than memory for a pure list of long words, and that in mixed lists of short and long words, memory for short and long words is equivalent, and is at the level of memory for a pure list of short words (Hulme, Stuart, Suprenant, Bireta, & Neath, 2004). We can assume that emotional pictures are also more distinctive than neutral pictures because of all of the unique operations involved in their encoding. Therefore, if we apply the same logic to the recall of emotional and neutral pure and mixed lists, SIMPLE appears to predict the mirror image of the empirical emotional list composition effect: that memory for memory for pure neutral lists will be decreased, compared to all other conditions.

The emotional oddball effect is also reminiscent of semantic and perceptual oddball effects. In a striking demonstration, the same oddball effects are observed either when a picture of a nude model is the oddball item within a list of pictures of clothed models (the standard items), or vice versa. Therefore, it is reasonable to ask whether models developed to explain the generic oddball effect can also explain the emotional oddball effect –including the categorization-activation-novelty model, CAN (Elhalal et al., 2014) and SIMPLE (Brown et al., 2007) - as well as whether eCMR can account for non-emotional oddball effects. We did not conduct a model comparison and cannot therefore comment on whether eCMR is better or worse in capturing oddball effects compared to CAN and SIMPLE. The simulation we reported here suggests that the mechanisms that drive both may be similar, and distinguished only in the degree of attention allocated to the oddball, and the degree to which it disrupts the temporal context of encoding. These dimensions can be crossed in an empirical investigation, for example using emotional and neutral oddballs that attract varied amount of attention and disrupt the temporal context to varying degrees. eCMR did make some unique predictions that could be tested empirically to support it against competing models of the oddball effect. First, eCMR predicted increased retrospective time estimation in oddball compared to control lists, which could be modulated by emotionality. Second, while memory impairment for items nearest the oddball is common to many models, eCMR uniquely predicted that this impairment is not a result of increased attention to the oddball. Ultimately, the success of eCMR compared to other models will be revealed by data that test these novel predictions.

5.2 Limitations of the modelling approach and plans for future research

The emotional experiences of our lives are rich with personal meaning that defines us as people and connects us to others and to the cultures we live in. They can be positive or negative, happy or calm, fearful or disgusting, and motivate us to approach, avoid, or otherwise behave in multiple bewildering ways. The controversy around defining emotion is well-known (Izard, 2010) and there is no sign yet for an umbrella theory that can bridge the gaps between the different theoretical positions that give rise to the disparate definitions. eCMR simplifies matter by considering only two aspects of emotional experiences – the semantic association between them and their increased intensity, which participants readily rate higher on a calm-to-arousing scale (Bradley & Lang, 1994; Feldman Barrett, 2016; Lindquist, Satpute, Wager, Weber, & Barrett, 2015; Russell, 1980). Yet even arousal was only represented in eCMR inasmuch as it drove enhanced attention. One aspect of emotional experience that deserves additional consideration is valence, because there is evidence that negatively-valenced stimuli are remembered better than positive ones even when attention is controlled (Kensinger, 2009a) and that valence may modulate some of the effects we discussed, including the relationship between attention and memory in mixed lists (Talmi, Schimmack, et al., 2007) and the effect of oddballs on surrounding items (Hurlemann et al., 2005). Future research should test whether the empirical results that we drew on here replicate with positive, arousing stimuli. eCMR can be extended to represent a valence dimension of context, if such results imply that this is necessary. It would be important for future research to control the semantic associations within and across valence categories, because there is evidence that positive experimental stimuli and autobiographical memories are judged to be more similar to each other than those that have a negative valence (Koch, Alves, Krüger, & Unkelbach, 2016).

The concept of an emotional dimension of similarity, which has been so useful in eCMR, deserves further research. Our previous work (Talmi & Moscovitch, 2004) inspired researchers to equate the semantic relatedness of the emotional and neutral stimuli they use. The problem with this approach, which we have used extensively ourselves, is that when stimuli are emotional, semantic relatedness ratings may reflect a different construct than they do when stimuli are neutral. Judgements of similarity may be influenced both by semantic associations and by emotional associations related to how stimuli make participants feel. Participants may therefore rate two negative stimuli, for example, two sad facial expressions belonging to two different people, as more related than a sad and a neutral expression belonging to the same person. How these dimensions of similarity are weighted is a topic that would benefit from further investigation. Notwithstanding that, the qualitative mechanisms of binding and competition that we investigate here are robust to quantitative variation in the degree of similarity across items.

eCMR was confined to the simulation of free recall, and in that, like other models, it neglects influences that arise from the nature of the memory test. The advantage of emotional stimuli that we highlighted here would, however, influence any test that benefits from memory for the temporal context of encoding. Although items do may not compete with each other in a recognition test as they do in free recall, the decision to classify a memory trace as a 'Remember' response is inherently defined as the degree to which the encoding context is retrieved at test. This may explain why emotion enhances measures of recollection more than familiarity (reviewed by Yonelinas & Ritchey, 2015). The integration of emotion into retrieved context models help us decipher an intriguing, recent dataset, where neutral stimuli that were encoded after a block of emotional stimuli were recollected better than neutral stimuli encoded before a block of emotional stimuli, before a block of neutral stimuli, or after a block of neutral stimuli (Tambini et al., 2017). We comment on this study because as in the emotional list composition effect, here, too, the key comparisons are between conditions that include only neutral items and those that mix emotional and neutral ones, and neutral memory changed based on the presence of emotional items. Following principles of retrieved context models, when emotional stimuli retrieve their temporal context during the recognition test, this might help items that share their encoding context retrieve it during the test. This could increase the recollection of neutral items that are studied close after, but not before, the emotional items, because only those share the temporal context of emotional items. In addition, it is likely that participants were still aroused when they encoded neutral items after an emotional block, because the physiological effects of emotional arousal linger for many minutes (Dickerson & Kemeny, 2004), resulting in shared source context as well; and that the arousal state will have increased attention participants allocated to retrieved memory traces (Mather et al., 2015). Therefore, there are a number of reasons compatible with eCMR that could account for the findings, but these speculations could only be examined when eCMR is extended to recognition memory tests.

Another major avenue for future development of eCMR is to simulate the effect of emotion on associative memory. The main challenge is to understand the fact that when participants are re-presented with an emotional item that they have encoded earlier, they are better at retrieving some aspects of the context of encoding, with a consequent increase in accurate Remember judgments, but not other aspects of the context, such as the orienting task that was performed during encoding, or other items that were encoded close in time and space (Bisby & Burgess, 2013; Madan et al., 2012, 2017; Sharot & Yonelinas, 2008; Yonelinas & Ritchey, 2015). These latter results appear to challenge eCMR because of the key role that increased item-context binding plays in the model. Retrieved context models do not, at present provide a comprehensive account for associative memory, although there has been preliminary attempts to do so (Davis, Geller, Rizzuto, & Kahana, 2008; Howard, Jing, Rao, Provyn, & Datey, 2009). Because we did not simulate Remember-Know or cued-recall tests, eCMR cannot directly speak to these points. Yet it is important to consider that the predictions of eCMR depend on the interplay of encoding and retrieval effects, and that, crucially, participants encode all aspects of the context of emotionally-arousing items differently than they do the context of neutral items. For example, an emotional element of a complex stimulus is thought to deprioritise other elements of the stimulus (Mather et al., 2017; Mather & Sutherland, 2011). When an emotional item itself captures attention, this takes away from the attention allocated to other stimuli in the same scene (Kensinger, Garoff-Eaton, & Schacter, 2007; Riggs, McQuiggan, Farb, Anderson, & Ryan, 2011). Even the effort participants spend on integrating the emotional item with another member of the same pair is altered (Murray & Kensinger, 2012). It would be important to clarify how these altered encoding processes influence the parameters in eCMR before we can relate our results to findings from the associative memory literature.

Finally, retrieved context models do not have a dedicated consolidation module (but see Sederberg et al., 2011). The core claim is that at the algorithmic level of explanation, time-dependent interference and context changes and reinstatement are sufficient to explain the behavioural phenomena that are typically attributed to consolidation. Retrieved context models are models of the information processing considerations that give rise to memory performance, which therefore can be implemented in various ways neurobiologically. Thus, we by no means intend to deny the contribution of mechanisms such as replay or time- or sleep-dependent change in the brain structures that maintain memory traces and even the very structures of synapses that store individual memories (McKenzie & Eichenbaum, 2011). These are simply outside the scope of our model. Future, more neurobiologically minded work might clarify how these neurobiological mechanisms might implement the computations proposed in eCMR, and conversely the eCMR computations might inform the investigation of the neurobiological mechanism. The step we took in section 3, where we ask how delay might change the nature of memory traces and the operation of retrieval mechanisms, has been inspired by behavioural and neurobiological findings about the way that memories are transformed with time delay, but is similarly blind to the actual mechanism that implement such transformations. Instead, the possibility that an increased reliance on non-temporal dimensions of similarity renders memories more schematic with time can be best tested by its fit to behavioural data, even if it is fundamentally inspired by findings that older memory traces rely less on the hippocampus and more on the neocortex (Moscovitch et al., 2016). Crucially, because eCMR can explain both immediate and delayed effects of emotion, it is the first model of emotional memory that encompasses both parsimoniously, but at the cost of a disconnection from the implementation level of explanation.

5.3 Concluding remarks

We know that memory performance is not simply a read-out of encoding and maintenance operations, but a reconstruction on the past in the service of current goals (Schacter & Addis, 2007). The current modelling suggests new directions for understanding the adaptive role of emotional memory enhancement in guiding behaviour. These effects have long been understood in terms of prioritizing which individual items to encode and maintain, but situating them within retrieved context models sheds new light on how emotional effects on retrieved memories might support decision making. We have already noted the striking formal correspondence between item-context associations (as inferred from recall tasks and embodied in retrieved context models) and predictive world models that have been separately proposed (and verified; Momennejad et al., n.d.) to underlie the evaluation of candidate actions in decision tasks (Gershman et al., 2012). In brief, the stored learned set of item-context associations amounts to a predictive world model that connects items, situations or events to others they tend to predict. In a decision task, these links can be retrieved at choice time to support a mental simulation of the likely consequences of candidate actions (Shohamy & Daw, 2015). In this framework, the new effect here of emotional modulation of these associations in eCMR would serve to highlight emotionally salient consequences, tending to give them a larger effect on one's deliberations. This, in turn, formally relates these emotional memory enhancements to a set of computational mechanisms and empirical effects (e.g., Huys et al., 2012) that have been proposed to underlie both adaptive control of prospection and maladaptive dysfunction, such as rumination and worry (Eldar et al., 2016; Huys, Daw, & Dayan, 2015) in disorders of mood.

The core claim of retrieved-context theory, that the conditions of retrieval crucially influence which items are recalled, was extended here to memories that are have a personal, emotional meaning. The important role of the retrieval stage in accessing these memories resonates particularly well with the motivations that drive much emotional memory research: to relieve the suffering that sometimes results from aversive emotional memories, on the one hand, and to extract neutral information about events that are dominated by emotional experiences, on the other. The applied clinical and forensic value of our modelling approach stems from its potential to inspire psychological manipulations to alter the accessibility of emotional and neutral memories, even long after the original experiences.

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APPENDIX 1: DETAILS OF METHODS IN TALMI ET AL.'S (2007) EXPERIMENT 2, SIMULATED IN SECTION 2

In simulations 1-3 we use three variants of eCMR to capture the average recall data from the emotional and related-neutral conditions in Talmi et al., 2007, Experiment 2. The semantic coherence of the stimuli used in that experiment was matched, first, by selecting neutral items that depicted domestic scenes, and second, by equating the semantic similarity ratings of emotional and neutral stimuli obtained in a separate rating study.

In the rating study an independent sample of 13 participants were presented with four sets of 40 pictures. Each set included 40 pictures: 10 emotional negative, 10 related neutral pictures which were all depictions of domestic scenes, 10 random neutral pictures, and 10 positive pictures. The pictures were drawn from the IAPS (Lang & Bradley, 2007) and supplemented by pictures from the Internet obtained using Google image search. Participants were given instructions explaining what semantic relatedness meant, contrasting it to perceptual relatedness, and rated all possible pairs within a subset on a 1 (unrelated) - 7 (highly related). Reliability analysis of ratings within each picture type, across the 4 sets (all negative-to-negative ratings, etc.) resulted in the exclusion of one participant. For the purpose of the 2007 study, several subsets of five pictures from these sets were selected, and a semantic relatedness score was computed for each picture in the subset based on its relatedness to the other 4 pictures in the same subset. Each list in the main experiment included three such subsets. The same pictures were used across the pure and mixed list conditions. The pure lists included 3 subsets of emotional negative pictures; 3 subsets of related neutral pictures; or 3 subsets of randomly selected neutral pictures. The mixed lists included one subset from each of these categories. There was no significant difference between the average semantic relatedness of the emotional and the related-neutral pictures, but the relatedness of random-neutral pictures was lower. The order of pictures in a list was randomised for each participant.

In that experiment two groups of participants studied either 3 pure lists or 3 mixed lists of 15 experimental pictures. Experimental pictures were preceded by two buffer stimuli of the same type (or one emotional and one neutral, in mixed lists), and followed by a minute-long arithmetic distractor task, after which participants recalled the pictures by describing the content of the pictures they have seen in writing. Each recall output was scored as 'correct' if two independent raters agreed that the description matches that of one, and only one, of the pictures in the study set. In the rating study participants were presented with subsets of 5 pictures; all pictures in a subset were drawn from the same category (emotional negative, related neutral pictures which were all depictions of domestic scenes, random neutral pictures). The pictures were drawn from the IAPS (Lang & Bradley, 2007) and supplemented by pictures from the Internet obtained using Google image search. Participants rated all possible pairs within a subset on a 1-7 scale for their degree of semantic relatedness. A semantic relatedness score was computed for each picture in the subset based on its relatedness to the other 4 pictures in the same subset. Each list in the main experiment included three such subsets. The same pictures were used across the pure and mixed list conditions. The pure lists included 3 subsets of emotional negative pictures; 3 subsets of related neutral pictures; or 3 subsets of randomly selected neutral pictures. The mixed lists included one subset from each of these categories. There was no significant difference between the average semantic relatedness of the emotional and the related-neutral pictures, but the relatedness of random-neutral pictures was lower. The order of pictures in a list was randomised for each participant.

APPENDIX 2: DETAILS OF METHODS FOR THE INSTRUCTED RECALL EXPERIMENT, REPORTED IN SECTION 2

We manipulated retrieval of mixed lists of negatively valenced emotional and neutral pictures by asking participants to recall emotional or neutral items first (the 'emotional first' and 'neutral first' conditions), comparing the results to a 'natural' mixed recall where no such instructions were given. Three groups of 18 participants took part in this experiment for course credit. They were 18-35 years old and were screened for neurological and psychiatric history. Each group studied 3 mixed lists of 10 negative and 10 neutral pictures, presented in a random order. The first list was always a practice list, and included unrated practice pictures, used in the practice portion of the Talmi et al. (2007) study. Each of the two experimental lists included the 'emotional negative' and the 'related neutral' pictures from one of the sets produced in the rating study reported in Talmi et al. (2007; describe above in **APPENDIX 1**). A semantic relatedness score was computed for each picture in the list based on its relatedness to the other pictures in the same set. The semantic relatedness of the negative and related-neutral pictures in each experimental list was equivalent. Note that the semantic relatedness score can be computed in multiple ways; if we only consider the relatedness of the negative and realted-neutral pictures (those that were actually included in the experiment), the relatedness of negative pictures was slightly but significantly higher than the relatedness of related-neutral pictures.

Participants were informed that they will be viewing negative, arousing pictures and neutral pictures of domestic scenes, and that the order of recall would vary. The first recall in all groups was 'natural'; data from this practice list was discarded. The next two lists were allocated to the same between-participant condition, either natural, emotional first, or neutral first.

When participants encode lists of stimuli that include emotionally arousing ones, the post-encoding emotional context is invariably more emotional than it was before the list was studied. This emotional coloration of the time-of-test context cue before any item is actually retrieved could render emotional stimuli more accessible than a context of a delayed retrieval test, biasing recall to commence with the retrieval of an emotional stimulus first. Therefore, a minute-long arithmetic distractor task separated the study and the picture free recall task to bring the emotional sub-region of the test context back to neutral.

The ‘natural’ mixed recall group were given 3 minutes to recall all of the pictures at any order. After those 3 minutes have elapsed, participants were invited to continue recall for another 3 minutes, although most participants could no longer recall anything more at that point, and data for that group was aggregated across these two test periods. The ‘emotional first’ group was given 3 minutes to recall the emotional pictures (first recall test). After 3 minutes, they were asked to recall the neutral pictures for another 3 minutes (second recall test). The ‘neutral-first’ group was asked to recall the neutral pictures first (first recall test). After 3 minutes, they were asked to recall the emotional pictures for 3 minutes (second recall test).