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Recollective and non-recollective processes in working memory retrieval

Fiona Laura Rosselet-Jordan [a,b,*], Marlène Abadie [b], Stéphanie Mariz Elsig [a], Pierre Barrouillet [c], Valérie Camos [a,*]

[a] University of Fribourg, Switzerland
[b] University of Aix-Marseille, France
[c] University of Geneva, Switzerland

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ABSTRACT

The aim of this study was to investigate the nature of the processes involved in working memory (WM) retrieval by distinguishing between recollective (direct access) and non-recollective (reconstruction) recall. To this end, the trichotomous theory of recall (Brainerd et al., 2009) was applied to young adults' recall performance in a complex span task in which word lists were presented in three successive study-test trials. In three experiments, factors known to affect WM performance were manipulated, such as the cognitive load (CL) of the concurrent task and the involvement of long-term memory (LTM) knowledge through the associative relatedness of the memory items and the temporally spaced presentation of memory lists. The application of the trichotomous theory of recall proved effective and established that both recollective and non-recollective processes support WM recall, though recollective processes are predominant. The detrimental effect of increased CL on recall performance appeared to result from a reduction in direct access, while leaving reconstruction unaffected. Two manipulations aimed at increasing the involvement of LTM in recall had different effects on retrieval processes. Associative relatedness favored direct access, while spaced presentation reduced it. The implications of these findings for our understanding of the relationships between LTM and WM and for WM theories are discussed.

The advent of the cognitive revolution in the middle of the last century disseminated the view of the mind as an information processing system. As Miller et al. (1960) emphasized, such a conception made necessary the hypothesis of a buffer able to maintain for at least some seconds relevant information in a state appropriate for its processing. Working memory (WM), the term they coined to describe such a buffer, has consequently been usually defined as a limited-capacity system responsible for the online maintenance of information in the service of ongoing processing (Baddeley, 1986; Baddeley & Hitch, 1974). While the mechanisms supporting online maintenance of information in WM have been the object of several investigations and debates (Barrouillet & Camos, 2015; Camos, 2017; for reviews), the processes underlying the retrieval of this information for immediate use have been less examined. The aim of this study was to investigate the nature of these processes.

1. Retrieval from WM

At first glance, the process of retrieval from WM may seem rather straightforward. It could be surmised that the content of WM, as it has often been assimilated with conscious awareness, is necessarily directly accessible and accurately reportable (Baars & Franklin, 2003; see also Andrade, 2001; Baddeley, 1993, 2000; Barrouillet & Camos, 2015, 2021). For example, in the most famous WM model, Baddeley (2000)'s multi-component model, memory traces are stored in distinct subsystems depending on their nature (i.e., the phonological buffer, the visuospatial sketchpad or the episodic buffer) from which they are directly retrieved for recall. Similarly, in the Time-Based Resource-Sharing (TBRS) model, memory traces are retrieved from a phonological or an episodic buffer (Barrouillet & Camos, 2021).

However, things might not be that simple. Other models assume that WM consists of long-term memory (LTM) items that are activated above threshold and whose accessibility depends on their level of activation (Anderson, 1993; Anderson et al., 1996; Cowan, 1999, 2005; Engle et al., 1999; Oberauer, 2002). For example, Cowan (1999) argued that, because memory traces do not remain activated long, retrieval must race against forgetting. If the activated memory representation has disappeared, its retrieval remains nonetheless possible if a sufficient episodic memory trace has been stored. Accordingly, several models

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* Corresponding authors at: Department of psychology, University of Fribourg, Rue P.A. de Faucigny, 2, 1700 Fribourg, Switzerland.
E-mail addresses: fiona.rosseletj@gmail.com (F.L. Rosselet-Jordan), valerie.camos@unifr.ch (V. Camos).

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assume a hierarchical organization of WM in which only three or four highly activated elements held in a focus of attention (Cowan, 2005) or a region of direct access (Oberauer, 2002) are highly activated and directly accessible. This central region is surrounded by an activated LTM area containing less activated items that can nonetheless be retrieved, but only indirectly through associations with items in the more central regions (Oberauer, 2002). Thus, several theories converge towards the idea that WM goes beyond the limited number of items that can be maintained in a highly activated state ensuring their direct accessibility, and assume that WM performance depends also on items that are less directly accessible, but nonetheless retrievable.

This conception is best exemplified by Unsworth and Engle (2007) who suggest that WM limitations arise from two components. The first is a dynamic attention component able to actively maintain a maximum of about four items in a primary memory akin to the focus of attention or the region of direct access mentioned above (Unsworth et al., 2010). However, when more than four items are present, as in simple span tasks involving long lists of six or seven items, items currently within primary memory are displaced into secondary memory from which they must be recalled through a cue-dependent search process. The same occurs in complex span tasks such as the reading span (Daneman & Carpenter, 1980) or the operation span tasks (Turner & Engle, 1989) in which the secondary task of reading sentences or solving equations occupies primary memory, thus displacing items to secondary memory. According to Unsworth and Engle (2007), whereas information in primary memory is directly accessible, retrieval from secondary memory requires a complex process involving the generation of a search set from some retrieval cues (e.g., learning context, serial positions, gist representation), as well as a discrimination process to differentiate between relevant and irrelevant items that can enter this search set through spreading activation or proactive interference. Thus, retrieval from WM goes beyond direct access of items in a heightened state of activation to involve more complex search processes among relevant and irrelevant items.

2. Recollective and non-recollective processes

The idea that retrieval in WM tasks is controlled by at least two mechanisms, one in which retrieval is relatively effortless because it is as if items were simply read out of consciousness, and the other in which retrieval uses partial information about studied items that requires an additional search operation, is reminiscent of the dual-process debate in LTM studies with the distinction between recollective and non-recollective retrieval. This distinction was first introduced and studied within the old/new item recognition paradigm (Mandler, 1980) through procedures like remember/know judgments (Tulving, 1985), confidence judgments (Yonelinas, 1994, 2002) or the process dissociation procedure (PDP; Jacoby, 1991, 1998; Jacoby et al., 1993). However, the dual-process retrieval approach has been recently extended to recall, which would rely on two dissociated retrieval operations, direct access and reconstruction (Barnhardt et al., 2006; Brainerd et al., 2002; Brainerd et al., 2003; Reyna & Mills, 2007). Direct access, which retrieves verbatim traces of individual items from the study list, is the faster and the more accurate of the two retrieval processes (Barnhardt et al., 2006). It proceeds by reinstating the surface form of the item that can be recalled by "merely reading out this surface information that echoes in the mind's ear or flashes in the mind's eye" (Brainerd et al., 2009, p. 786). This direct access is clearly the process by which information is retrieved from primary memory in Unsworth and Engle's (2007) model, the focus of attention in Cowan's (2005) model, the region of direct access in Oberauer (2002), as well as from the episodic buffer in Baddeley's (2000) and Barrouillet and Camos' (2015) TBRS model.

By contrast, retrieval by reconstruction of memory traces is a non-recollective process that regenerates targets from partial-identifying information, and especially from their meaning content captured in gist traces (Brainerd et al., 2009). However, this partial-identifying information does not point to a unique target but generates a set of candidates (e.g., remembering that some fruit was presented might recover candidates such as "orange", "banana", "apple", and "lemon", when only "lemon" was studied). Thus, reconstruction is followed by a judgment step. Reconstructed items are assumed to generate familiarity signals, with a given item being output if the strength of its familiarity signal exceeds some decision criterion. This reconstruction process clearly corresponds to the cue-dependent search process that retrieves memory traces from secondary memory in Unsworth and Engle's (2007) model.

Thus, although one might have imagined at first glance that retrieval from WM would rely primarily on direct access and recollective processes, non-recollective processes might be more prevalent than expected. Indeed, if the concurrent processing involved in complex span tasks occupies primary memory and displaces its content into secondary memory from which memory items are retrieved, as Unsworth et al. (2010) assume, retrieval in WM tasks should frequently rely on reconstructive and non-recollective processes.

3. Previous investigations of dual processes in WM retrieval

Several studies have already addressed the nature of the processes governing retrieval from WM. Using the PDP, Hedden and Park (2003) studied in young and older adults the recognition of target word-pairs under the retroactive interference created by reading of other distractor word-pairs. They found that recollection decreases with age in verbal WM performance, whereas familiarity increases. Greene and Naveh-Benjamin (2022) reported congruent results using a continuous associative recognition task. Specifically, older adults exhibited some losses in the ability to engage recollection-rejection processes, which consist in rejecting items that share meaning with previously encountered items, in a short-term test. The same conclusion was reached by Oberauer (2005) who investigated the relationship between WM capacity and the resolution of conflict between familiarity and recollection in short-term recognition tasks such as Sternberg and n-back tasks. Older adults, as well as individuals with low WM capacity, showed disproportionately lower performance on intrusion probes, suggesting that both aging and low WM capacity are characterized by a deficit in content-context binding that usually subserves recollection (see Schmiedek et al., 2009, for a related observation). In young adults, Abadie and Camos (2019), using a Brown-Peterson task followed by an immediate recognition test, demonstrated that 88 % of correct recognition responses were based on retrieval of verbatim representations, memory traces that are retrieved through recollective processes (see Rousselle et al., 2023, for a similar observation in children). The conclusion that WM is related to efficiency of recollection but not familiarity has also been reached by Unsworth and Brewer (2009) using a delayed free recall task. Although these studies shed light on WM retrieval and the prominent role of recollection on this process, they remain limited by their reliance on recognition (Abadie & Camos, 2019; Greene & Naveh-Benjamin, 2022; Hedden & Park, 2003; Oberauer, 2005; Rousselle et al., 2023) or free recall paradigms (Unsworth & Brewer, 2009; Unsworth & Engle, 2007). These paradigms are not among those commonly used when studying WM, probably because they do not mimic the interplay between processing and storage with self-initiated access to previously stored information that characterizes WM functioning as traditional recall paradigms such as complex span or Brown-Peterson tasks do.

We are only aware of a single study having analyzed WM retrieval processes in such paradigms (Loaiza et al., 2015). Loaiza et al. used the process dissociation procedure (PDP) in a task in which participants had to maintain series of five digits while solving a reasoning problem after each digit. In the inclusion condition, they were asked to recall the five presented digits in any order, whereas in the exclusion condition, they were instructed to recall those digits that were *not* presented. Following an observation by Barrouillet et al. (2013), the presentation time of the digits (remaining on screen either 1 s or 3 s) was manipulated to vary the level of activation of the memory items in WM. The PDP analysis revealed the independent contributions of recollection and familiarity to complex span performance. Longer presentation times increased recollection estimates, while leaving familiarity estimates unchanged, these latter estimates being far less reliable than recollection. These results were replicated in a Brown-Peterson paradigm. Although this study mainly confirms the role of recollection in WM retrieval, some aspects of its design could undermine its conclusions. Indeed, the PDP method used by Loaiza et al., which is inspired from a study by McCabe et al. (2011), relies on the assumption that exclusion errors result from familiarity-based automatic process. However, due to the highly restricted size of the set from which memory items were drawn (i.e., the 10 digits), the production of a studied digit in the exclusion condition of Loaiza et al.'s procedure is difficult to attribute to an automatic familiarity-based process, thus undermining the rationale of the PDP. Moreover, process dissociation techniques have themselves been criticized as unreliable methods for separating recollective and non-recollective retrieval (Ratcliff et al., 1995; Wixted, 2007).

Overall, although retrieval is one of the main functions of WM, the processes involved in this key mechanism remain largely unexplored. In the following, we present a theory of recall along with a mathematical model that has the advantage to allow for an estimation of recollective and non-recollective processes from recall performance in tasks routinely used in WM studies such as complex span tasks, without any need to collect metacognitive judgments or to introduce unusual recall instructions such as exclusion conditions.

4. The trichotomous theory of recall

Proposed by Brainerd et al. (2009), the trichotomous theory of recall subsumes the traditional dual-process distinction between recollective and non-recollective remembering (Mandler, 1980; Tulving, 1985), encompasses all of the standard recall paradigms (cued, free, paired-associates, serial) and has already been successfully applied to cued, free, and paired-associates recall tasks in groups of various ages and cognitive impairments (Brainerd et al., 2009; Brainerd et al., 2012; Brainerd et al., 2014; Brainerd et al., 2015; Brainerd & Reyna, 2010). However, it has not yet been applied to serial recall as in WM complex span tasks. The strength of this model is that it can measure recollective and non-recollective processes without any recourse to metacognitive judgments such as Tulving's (1985) remember-know procedure or to manipulation of recall instructions as in the implementation of the PDP by McCabe et al. (2011) or Loaiza et al. (2015). What is only needed are the error-success data from a recall experiment with a design of the form S_1T_1, S_2T_2, S_3T_3, with 3 attempts of study (S) followed by a recall test (T). The basic model assumes that a given item of a recall task can be in three different states. At the beginning of the task (before S_1), all the items are in a no-recall state U in which the probability of correct recall is 0 (the items cannot be known before their first study, hence the null recall probability). Once study cycles have begun, the learning process can result in two distinct changes. A given item can escape U and enter either a partial-recall state P, in which its probability of correct recall is $0 < p < 1$, or a perfect-recall state L in which the probability of correct recall is 1. When an item reaches the state L, it will remain in this state for the following study-test cycles, contrary to state P from which an item can reach state L on a subsequent Study-Test (ST) sequence. The model works as a two-stage absorbing Markov chain in such a way that (a) once an item has escaped U, it cannot fall back to this state in further trials, and (b) L is an absorbing state such as once an item enters state L at a given trial, it cannot fall back to previous states and its recall is perfect for all the following trials. As a consequence, a minimum of three ST cycles is needed to follow the different changes of state of a memory item from an initial U state to the possible P or L states.

The dual-retrieval interpretation of these two learning states for recall tasks is that recollective and non-recollective retrievals correspond to the entry to state L and to state P, respectively. As we explained above, these two forms of retrieval involve different types of episodic traces that are defined within the fuzzy-trace theory (FTT, Reyna & Brainerd, 1995) as verbatim and gist traces, respectively. Verbatim traces correspond to the representation of the surface form of specific items and support recollective recall through direct retrieval. By contrast, gist traces do not point to a specific instance, but to sets of items because they do not grasp the surface form of the item but its meaning (for example, remembering that the list contained "pet bird" instead of "canary"). They support non-recollective recall through the reconstruction process described above. Because the first step of reconstruction that regenerates memory traces is followed by a judgment step based on familiarity evaluation, this means that state P can be partitioned into a substate P_C (the item is reconstructed *and* recalled), and a substate P_E, in which the item is reconstructed but recall fails (the familiarity signal does not reach the criterion).

The theory is embedded in a hidden Markov chain that measures the three processes (direct retrieval, reconstruction, and familiarity judgment) by assessing the parameters of the matrix of transition through the three-state space (U, P, and L) providing the better fit of the intertrial changes (from S_1T_1 to S_2T_2, and then S_3T_3) in the probability of correctly recalling the target items. The version of the model we used in the present study allows the assessment of six parameters (D_1, D_2, R, J_1, J_2 and J_3). Parameters D determine the probability for an item to enter state L, at the first (D_1) or at any subsequent trial (D_2). Parameter R refers to the probability to enter state P. Parameters J refer to familiarity and determine the probability that an item having accessed state P will be outputted or not, during the first trial (J_1), the second (J_2) and the third (J_3) trial. Brainerd et al. (2009); Brainerd & Reyna, 2010) have empirically verified the absorbing property of the model, as well as the fact that a two-stage model provides systematically a better fit than a single-stage model or any model with more than two stages. The model proved to provide a very good fit to data from a variety of free recall, cued recall and paired associates recall tasks in children, adolescents, young and older adults.

5. The present study

The trichotomous theory provides the machinery needed to assess the respective role of direct access and reconstruction in WM tasks. For this purpose, the model was applied in the present study to a complex span task in which participants studied series of six words for further serial recall, each word being followed in 4 s inter-word intervals by a concurrent task consisting of reading aloud a series of digits appearing successively on screen. In order to obtain estimates of the parameters of the model, each series of words was presented for three successive study-test (ST) cycles in a design of the form S_1T_1, S_2T_2, S_3T_3.[1] This study being a first attempt to apply the trichotomous model to the complex span task paradigm, its main aim was to test the ability of this model to fit recall data from a WM task, and to assess the relative contribution of recollective and non-recollective retrieval processes in WM. The expectations concerning this relative contribution differ from one model of WM to another. For example, the multi-component model (Baddeley, 2000) and the TBRS model (Barrouillet & Camos, 2015, 2021) would assume that recall from WM depends on the recollection of memory traces actively maintained in some episodic buffer, whereas the primary-secondary memory framework (e.g., McCabe, 2008; Unsworth & Engle, 2007) would emphasize the importance of non-recollective processes through cue-based search and selection from secondary memory traces.

We also investigated the impact on these processes of factors known

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[1] As in Gomes et al. (2013; 2014), the original procedure of Brainerd et al. (2009; 2010), that involved two successive recall tests (T_1T_2) after S_1, before a S_2T_3 cycle, was slightly adapted. Indeed, the insertion of a T_2 far away from S_1, and separated from S_1 by a first recall test T_1, could have modified WM content and distorted its assessment.

to have a strong impact on WM performance, namely the cognitive load (*CL*) of the secondary task and the availability of LTM knowledge about the memoranda. Concerning the former of these factors, *CL* is conceived within the TBRS model as the proportion of time during which the secondary task occupies attention, thus preventing the refreshing of decaying memory traces (Barrouillet et al., 2004; Barrouillet & Camos, 2021). It has been demonstrated in several studies that increased *CL* results in poorer recall performance (Barrouillet & Camos, 2012, 2015, for reviews), an effect considered as a benchmark for models of short-term and working memory according to Oberauer et al. (2018). The question under study was to determine what kind of retrieval (i.e., recollective or non-recollective) is more affected by *CL* variations that were introduced by presenting either 3 or 6 digits to be read in the 4 s inter-word intervals for low and high *CL*, respectively. Our prediction was that variations in *CL* should mainly affect the recollective processes underpinning direct retrieval. Indeed, if refreshing memory items consists of reinstating their verbatim traces (Barrouillet & Camos, 2021), preventing refreshing to take place should hinder the retrieval process based on verbatim traces (i.e., direct access), while leaving gist representations and the associated non-recollective processes largely unaffected. Consistently, other studies in the field of normative decision making have shown that only verbatim traces retrieval was affected by an increase in the *CL* of a secondary task performed during a retention interval of a few minutes, while gist memory was not affected (Abadie et al., 2013, 2017). Alternatively, within the primary-secondary memory framework in which recall in complex span tasks involves retrieval from secondary memory, higher *CL* would result in more frequent displacement of memory items in secondary memory. Thus, recall under higher *CL* should be associated not only with a decrease in recollective processes, but also with a more frequent recourse to non-recollective recall through reconstruction. Experiment 1 was aimed at testing these hypotheses.

Concerning the potential effect of LTM knowledge, several studies have established the existence of so-called LTM effects in short-term and working memory, such as the effects of lexicality (words are easier to recall than pseudowords), frequency (frequent words are easier to recall than rare words), or concreteness (concrete words are easier to recall than abstract words) (e.g., Camos et al., 2019; Hulme et al., 1991; Hulme et al., 2003; Loaiza & Camos, 2018; Poirier et al., 2011; Saint-Aubin & Poirier, 1999). Our interest in the present study was primarily in the associative relatedness effect, the fact that lists of related words are better recalled than lists made of unrelated words (Rosselet-Jordan et al., 2022; Saint-Aubin et al., 2005; Saint-Aubin & Poirier, 1999; Tse, 2009; Tse et al., 2011). Lists of associatively related words consist of words that do not belong to the same taxonomic category, but are strongly related due to their frequent co-occurrence in events or situations (e.g., *rabbit-carrot-ear*; Brainerd et al., 2020; Coane et al., 2021; Tse et al., 2011). Our study focused on the latter type of associative relatedness, which is mainly based on the recurrent use or appearance of these words together.

It has often been assumed that LTM effects on immediate serial recall are due to a process of redintegration occurring at recall (Hulme et al., 1997; Schweickert, 1993). A comparison process between degraded memory traces and knowledge available in LTM would allow their restoration. Such a mechanism could account for the associative relatedness effect, long-term knowledge supporting the restoration of degraded phonological traces (Saint-Aubin & Poirier, 1999). Accordingly, this redintegration process by which memory traces are restored using semantic information is akin to a reconstructive process. Consequently, the better recall of associatively related words would be due to a higher contribution of reconstructive retrieval processes when lists of related rather than unrelated words are to be remembered. In line with this prediction, several studies have shown that the advantage of associatively related over unrelated words in long-term recognition is underpinned by a strong increase in the retrieval of gist memory that rely on reconstructive processes (Abadie et al., 2021; Abadie & Guette, 2024; Brainerd et al., 1999, 2001; Stahl & Klauer, 2008). This hypothesis was tested in Experiment 2.

Finally, another way to investigate the impact of LTM on processes governing retrieval from WM could be to facilitate the creation of LTM traces of the memoranda presented in the complex span task; LTM traces that could have an impact on WM retrieval when word lists are presented anew. In Experiments 1 and 2, the three *ST* cycles for each list of words were administered in immediate succession. The first list was the subject of a complete S_1T_1, S_2T_2, S_3T_3 sequence before moving on to study and recall of second list, and so on. However, it could be imagined having the S_1T_1 cycle applied to all lists (S_1T_1 for List$_a$, List$_b$, …, List$_n$) before moving on to S_2T_2 applied to all lists, and finally S_3T_3. This procedure results in the introduction of intervals between two presentations of a given list, these intervals being filled with the learning of the other lists. Such a reinforcement schedule, compared with the immediate repetition as in Experiments 1 and 2, is known for a long time as being beneficial for long-term retention (Landauer, 1969; Underwood, 1961, see Cepeda et al., 2006, for a meta-analysis). Thus, it can be assumed that the spaced presentation of word lists would lead to worse immediate serial recall performance than the immediate repetition of the *ST* cycles used in Experiments 1 and 2, but to stronger LTM traces during their second and third presentation in S_2T_2 and S_3T_3. Hence, the spaced presentation of lists in Experiment 3 should result in better delayed-test recall. This strengthening of LTM traces should be especially true for the associatively related lists, as they would benefit from gist traces, which are better preserved in the long term than verbatim traces (e.g., Abadie et al., 2013, 2017; Abadie & Camos, 2019; Brainerd & Reyna, 2005). However, in immediate recall test, do these stronger LTM traces affect recollective or non-recollective processes? One can expect that any strengthening of LTM traces would help reconstructions, i.e., non-recollective processes.

6. Experiment 1

This experiment aimed to assess for the first time the role of direct access and reconstruction in WM tasks using the dual retrieval model of the trichotomous theory of recall. In a complex span task, participants studied six words, each followed by a concurrent reading digit task prior to serial recall in three successive study-test cycles S_1T_1, S_2T_2, S_3T_3. The main aim was to assess the relative contribution of recollective and non-recollective retrieval processes in WM. Although they did not always make specific predictions about the nature of the processes governing retrieval, WM models might diverge in their expectations. Models such as the multi-component and the TBRS models would predict that recall in WM tasks depends mainly on direct access, while the primary-secondary memory framework would emphasize the role of non-recollective processes. Moreover, this first experiment also assessed the impact of *CL* variations on retrieval processes. While the TBRS model predicts that an increase in *CL* would reduce the predominance of direct access to the verbatim traces of the items studied while leaving non-recollective retrieval intact, it would be expected instead, according to the primary-secondary memory framework, that an increase in *CL* would lead to less direct access but also to more reconstruction, i.e., non-recollective retrieval.

6.1. Method

Materials and data from all the experiments are available on OSF (https://osf.io/v4z2c/?view_only=03f39df0c1ae4698bc80ebb9209214d3). All the experiments conformed to the ethical standards of the declaration of Helsinki and were approved by the institutional review board of University of Geneva for Experiment 1 and of the University of Fribourg for Experiments 2 and 3 (number 350). All participants were native French speakers and signed an informed consent form prior to their participation.

6.1.1. Participants

Twenty-five undergraduate students (19 females and 6 males[2]; mean age = 21.9 years; *SD* = 4.1) at the University of Geneva received a partial course credit or CHF 20 for participating. The sample size was based on Barrouillet et al.'s (2004, 2007) experiments that provided evidence for a *CL* effect on complex span tasks.

6.1.2. Material

From the Lexique3 database (New et al., 2001), we selected 144 monosyllabic French nouns with a homogeneous frequency of occurrence ($M = 8.57$, $SD = 3.20$), from which 24 memory lists of six words were created. Half of the participants studied the words of 12 of these lists, whereas the other half studied the other 12 lists. For each participant, half of the lists were presented in the low *CL* condition and the other half in the high *CL* condition, with the assignment of lists to experimental conditions counterbalanced across participants. The 12 lists were presented in random order, participants being informed of the level of *CL* of the forthcoming list.

6.1.3. Procedure

Each list was presented in three successive *ST* cycles for a total of 36 trials per participant. Each trial began with the presentation of the word "Lent" or "Rapide" (i.e., "slow" and "fast" in French) for 1500 ms, informing participants of the pace of the digit presentation after each word for the low and high *CL* conditions, respectively. After a 100-ms blank screen, the first word was presented on screen for 800 ms, followed by a 200-ms blank screen and the interword retention interval of 4000 ms. During the retention interval, three or six digits (from 1 to 9) were presented for 1183 ms or 516 ms, for the slow and fast pace conditions, respectively, each followed by an interstimulus interval (ISI) of 150 ms. Then, the second word appeared for 800 ms, followed by the 200-ms blank screen and the 4000-ms retention interval, and so on until all six words of the list had been presented. Participants were asked to read the words and the digits aloud to prevent the use of articulatory rehearsal (Camos et al., 2009) and favor that of attentional refreshing (Camos et al., 2011), and to remember the words for later recall. At the end of the list, the word "Rappel" (recall in French) was displayed on screen. Participants were instructed to orally recall all the words in correct order, without any time constraints, and saying "Je ne sais pas" (I don't know) for any forgotten word. The same procedure was repeated over three *ST* cycles for each list. Following the first recall (T_1), participants studied the same list in the same condition again ($S2$) and recalled it (T_2) and did this a third time again (S_3T_3) before moving on to the next list. In the three *ST* cycles, words were always presented in the same order within their list. The experimenter remained with participants to note any errors or misses in the reading digit task. Prior to the experimental session, participants were familiarized with the task by performing two trials in each *CL* condition, each of which was repeated in three successive *ST* trials. Fig. 1 illustrates the procedure for one *ST* cycle in slow and fast pace conditions.

6.1.4. Transparency and openness

In this and the following experiments, we report how we determined our sample size, all data exclusions, all manipulations, and all measures in the study. All data are available on OSF (https://osf.io/v4z2c/?view_only=03f39df0c1ae4698bc80ebb9209214d3). Data were analyzed using JASP (0.17.1; Love et al., 2019) and TreeBUGS package (Heck et al., 2018) in R Statistical Software (v.2023.03.0; R Core Team, 2021). The design and the statistical analyses were not pre-registered.

6.2. Results

6.2.1. Recall performance

Mean and SD for each dependent variable are available on Table 1, and Table 2 shows the $BF_{inclusion}$ values for the main and interaction effects. A 2 (*CL* conditions: high vs. low) × 3 (trials) Bayesian repeated measures ANOVA with default values was run on the percentage of words recalled in correct position. In Bayesian hypothesis testing, the strength of evidence for a specified model (M1) was quantified by comparing this model against a null or reduced model (M0). The ratio of the likelihood of the two models under comparison is the Bayes Factor (BF_{10}). BF_{10} of each model was obtained by comparing it to the null model. Strength of evidence is evaluated using Kass and Raftery (1995) interpretation of Bayes Factors.

The best model was the full model, including the main effects of *CL*, trial, and the interaction between them, $BF_{10} = 3.61 \times 10^{28}$. However, this model differed only slightly in accounting for the data from the second-best model, which did not include the interaction, $BF_{10} = 1.76 \times 10^{28}$. For the sake of parsimony and because the $BF_{inclusion}$ for the interaction was below 3 (see Table 2), we considered the second model to be the best.

As shown in Table 1, not surprisingly, there was a strong effect of repetition among trials, rate of correct recall increasing from the first ($M = 42.6$, $SD = 16.5$) to the second ($M = 78.7$, $SD = 13.9$) and third trial ($M = 92.4$, $SD = 7.2$). Recall performance was also higher for low ($M = 74.5$, $SD = 12.0$) than high ($M = 67.9$, $SD = 13.3$) *CL*, replicating the *CL* effect previously observed in several studies (see Barrouillet & Camos, 2012, 2015, for reviews). It is worth noting that the *CL* effect was still significant in the last trial, as evidenced by Bayesian paired *t*-test comparing the two *CL*s, $BF_{10} = 9.4$.

6.2.2. Model fit and parameter estimations

An empirically validated two-stage Markov model (e.g., Brainerd et al., 2009; Brainerd et al., 2012; Brainerd & Reyna, 2010; Gomes et al., 2014, 2013) was used to quantify recollective (direct access, *D*) and non-recollective retrieval processes (reconstruction, *R*, and familiarity judgment, *J*). The model is depicted in Box 1. It consists of a starting vector (*W*) and an interstate transition matrix (*M*). In the case of three *ST* cycles, there are two transition matrices (from ST_1 to ST_2 and from ST_2 to ST_3). The parameters of *W* represent the probabilities of a studied item being in state *L*, P_E (for items in a *P* state that are not recalled), P_C (for items in *P* state and recalled), or *U* on the first recall test, whereas the parameters of *M* are the probabilities of an item transitions from one state to another in subsequent trials (see Box 1 for explanations).

Of the different versions of the dual retrieval model for measuring recollective and non-recollective processes that fit the data from the experiments with three *ST* trials, the alternative error model was the one that best fits the data from our three experiments.[3] Such model has two direct access parameters (D_1 and D_2), one reconstruction parameter (*R*) and three familiarity judgments (J_1, J_2 and J_3). It assumes that a given item can only access the *L* state after trial 1 (parameter D_2) following a previous recall failure, i.e., when the item was in state *U* or P_E on the previous trial, hence the name *error*.

Analyses were conducted using the latent-trait approach (Klauer, 2010). Parameters were estimated in the TreeBUGS package (Heck et al., 2018) in R Statistical Software (v.2023.03.0; R Core Team, 2021), using the program's default priors. The uncertainty of each parameter in each *CL* condition was quantified using a Bayesian estimation approach. The uncertainty of a parameter is expressed as the credible interval (CI) around its posterior estimate. A 95 % CI indicates the range within

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[2] In accordance with the ethical approval obtained for this study, only sex as a binary category and date of birth have been collected.

[3] The matrices of the different versions of the dual retrieval models tested and the model fit statistics of the data of the three experiments are available on the OSF (https://osf.io/v4z2c/?view_only=03f39df0c1ae4698bc80ebb9209214d3).

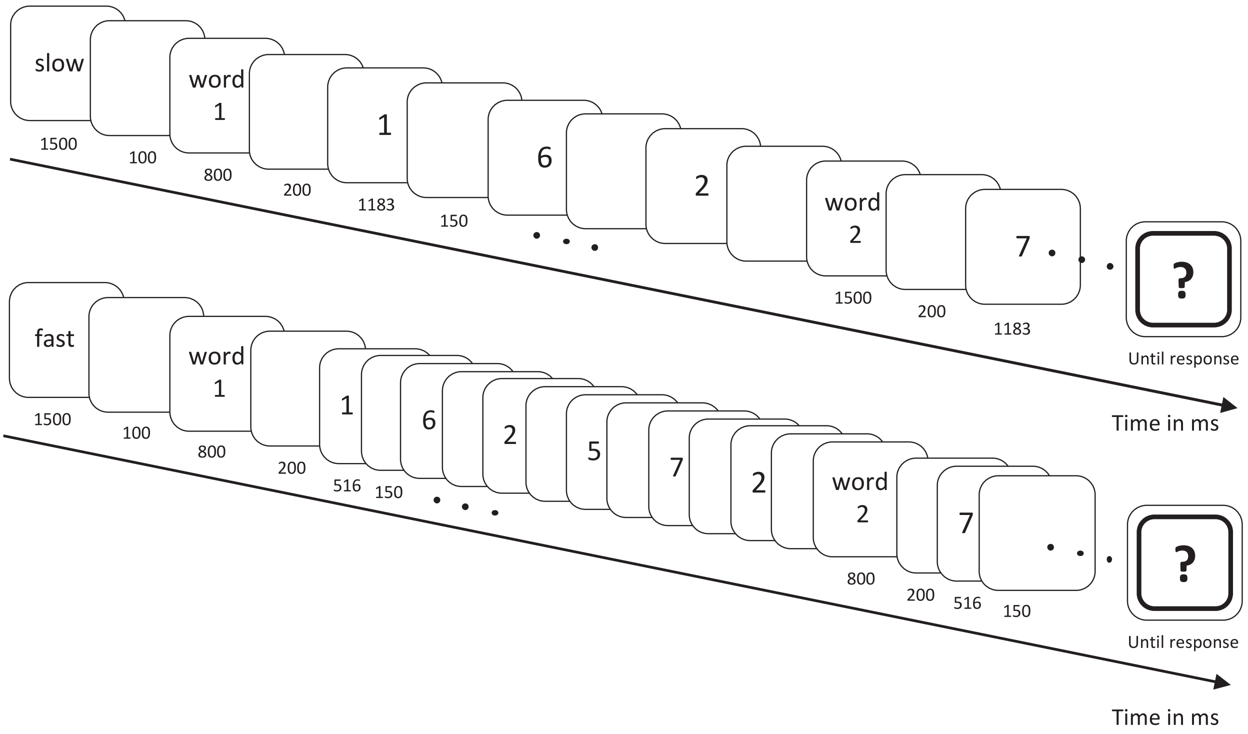

Fig. 1. Illustration of a trial in the slow pace (upper part) and fast pace (lower part) conditions.
Note. Each trial began with an indication of the pace of the reading digit task. Participants read aloud all words and digits until "Rappel" in Exp. 1 or a question mark in Exp. 2 and 3 appeared, which marked the beginning of serial oral recall.

Table 1
Mean percentage of correct recall (and SD) in Experiments 1, 2, and 3 as a function of cognitive load (low vs. high), trials (1st, 2nd and 3rd), and associative relatedness (unrelated vs. related) when manipulated (Exp. 2 and 3) for the different recall tests.

		Low Cognitive Load					High Cognitive Load				
		Immediate recall			Delayed recall	7-day delayed recall	Immediate recall			Delayed recall	7-day delayed recall
		Trial 1	Trial 2	Trial 3			Trial 1	Trial 2	Trial 3		
Exp. 1	Unrelated	47.8 (18.0)	80.6 (14.9)	95.1 (5.6)			37.3 (17.0)	76.8 (15.9)	89.6 (10.5)		
Exp. 2	Unrelated	50.3 (22.8)	83.1 (19.0)	93.1 (15.7)	18.6 (6.9)	7.5 (5.4)	44.8 (23.2)	75.3 (23.1)	90.1 (15.7)	17.3 (8.3)	7.0 (6.2)
	Related	63.1 (18.0)	89.4 (10.1)	94.4 (6.9)	32.0 (9.2)	20.0 (11.6)	61.6 (17.9)	84.5 (15.4)	93.2 (8.4)	31.5 (6.2)	21.9 (9.3)
Exp. 3	Unrelated	49.9 (15.0)	67.0 (18.8)	79.7 (15.9)	57.8 (23.8)	29.9 (18.1)	39.7 (18.1)	60.7 (20.2)	74.1 (21.6)	56.0 (22.0)	29.6 (20.0)
	Related	66.0 (17.5)	84.7 (13.8)	93.6 (10.9)	82.1 (13.6)	65.2 (22.2)	59.0 (13.6)	79.2 (15.1)	92.4 (8.1)	85.1 (12.7)	59.9 (20.5)

Table 2
$\text{BF}_{\text{inclusion}}$ of all effects across matched models on the analysis of recall performance in Experiments 1, 2, and 3.

	Exp. 1	Exp. 2			Exp. 3		
Recall Test	Immediate recall	Immediate recall	Delayed recall	7-day delayed recall	Immediate recall	Delayed recall	7-day delayed recall
CL	**3.41×10^{1}**	**1.42×10^{2}**	0.24	0.27	**5.12×10^{3}**	0.19	0.34
Trial	**5.02×10^{26}**	**6.78×10^{42}**			**1.09×10^{42}**		
Relatedness		1.49	**1.37×10^{7}**	**5.09×10^{6}**	**2.57×10^{3}**	**1.12×10^{5}**	**2.61×10^{6}**
CL × Trial	2.05	0.90			0.28		
CL × Relatedness		0.58	0.25	0.41	0.34	0.43	0.40
Relatedness ×Trial		**8.23×10^{1}**			0.16		
CL × Trial × Relatedness		0.10			0.16		

which we can be 95 % sure that the true value of the parameter lies. Posterior predictive checks were computed to ensure the alternative error model fitted the data well. Correspondence between the posterior-predicted and observed means and covariances was computed via the T_1 and T_2 statistics, respectively (Klauer, 2010). Model fit is considered satisfactory when the posterior predictive p (PPP) value >0.05.

Box 1
Starting vector W and transition matrix M of the alternative error dual retrieval model.

		$L(1)$	$P_E(1)$	$P_C(1)$	$U(1)$
$W=$	U(0)	D_1	$(1 - D1)R(1 - J1)$	$(1 - D1)R\ J1$	$(1 - D1)(1 - R)$

		$L(2)$	$P_E(2)$	$P_C(2)$	$U(2)$
$M_1=$	$L(1)$	1	0	0	0
	$P_E(1)$	D_2	$(1 - D_2)(1 - J_2)$	$(1 - D_2)\ J_2$	0
	$P_C(1)$	0	$(1 - J_2)$	J_2	0
	$U(1)$	D_2	$(1 - D_2)R(1 - J_2)$	$(1 - D_2)RJ_2$	$(1 - D_2)(1 - R)$

		$L(3)$	$P_E(3)$	$P_C(3)$	$U(3)$
$M_2=$	$L(2)$	1	0	0	0
	$P_E(2)$	D_2	$(1 - D_2)(1 - J_3)$	$(1 - D_2)\ J_3$	0
	$P_C(2)$	0	$(1 - J_3)$	J_3	0
	$U(2)$	D_2	$(1 - D_2)R(1 - J_3)$	$(1 - D_2)RJ_3$	$(1 - D_2)(1 - R)$

Note: Matrices read in the following way. For example, in M_1, the probability from items in L after the first ST cycle, $L(1)$, is 1 to be in L state in the second ST cycle, $L(2)$, and null for $P_E(2)$, $P_C(2)$ and $U(2)$. Items in P state, but not recalled in ST_1, $P_E(1)$, (a) can remain in this state in ST_2, $P_E(2)$, with a probability of $(1 - D_2)(1 - J_2)$ (not directly retrieved and not familiar enough), (b) can reach L state in ST_2, $L(2)$, with a probability D_2, or (c) P_C state, $P_C(2)$, with a probability of $(1 - D2)\ J2$ (not directly retrieved but familiar), and (d) never fall back to U. Items in P state and recalled in ST_1, $P_C(1)$, remain in P state and are recalled, $P_C(2)$, or not, $P_E(2)$, in ST_2 depending on their familiarity, J_2 or $(1 - J_2)$. Finally, items that were in U state in ST_1, $U(1)$, can reach L state if directly retrieved, D_2, can move to P state if not directly retrieved but reconstructed, $(1 - D_2)R$, and being either recalled, $P_C(2)$, or not, $P_E(2)$, depending on their familiarity, J_2 or $(1 - J_2)$. They can also remain in U state if not directly retrieved, $(1 - D_2)$, and not reconstructed, $(1 - R)$.

Model fit was satisfactory, with PPP > 0.412 for all T_1 and T_2 statistics. Population-level parameter estimates are presented in Table 4. Overall, the majority of the recalled items were retrieved by direct access, with D_1 and D_2 values ranging from 34 to 70 % across trials and *CL* conditions. Reconstruction accounted for 25 to 60 % of the remaining retrievals.

6.2.3. *Parameter comparisons*

To examine the *CL* effect and compare parameters between *CL* conditions, difference scores were calculated by subtracting the posterior distributions of the high *CL* condition model from that of the low *CL* condition. We obtained a posterior mean difference and 95 % CI, indicating the range in which we can be 95 % sure that the actual difference lies. Following the recommendations from Smith and Batchelder (2010), we considered that if the 95 % CI of the difference score for a given posterior mean difference excluded 0, there was credible evidence for a *CL* difference. If the 95 % CI of the difference score included 0, the possibility that there was no difference in the parameter between low *CL* and high *CL* condition could not be ruled out. Difference scores obtained are given in Table 5. The only credible *CL* difference was for the direct access parameter during the first trial, D_1, which was higher in the low *CL* than in the high *CL* condition. It is worth to note that *D* parameters are estimated with higher reliability than *R* or *J*, which explains why a smaller difference in *D* led to reliable effect, while a much larger difference in *R* and *J* did not. Thus, the *CL* effect mainly affected recollective retrieval processes and had no impact on reconstructive processes.

6.3. *Discussion*

This experiment was the first attempt to apply the trichotomous model of recall to WM. The results revealed that the dual-process model of recall provides a very good fit of the data, extending the application of this model to WM, and confirming that these two distinct processes govern retrieval from WM. The first aim of this experiment was to shed light on the privileged retrieval process that underlies WM recall. The trichotomous model indicates that the recalled items in WM span tasks are mainly retrieved through direct access, while the use of reconstructive processes is less frequent but cannot be discarded, as indicated by the 95 %CI around the *R* parameter which, although wide and underlining an important interindividual variability, does not include 0. It should be noted that parameters *D*, *R* and *J* allow to compute the exact percentages of WM recall that are due to direct access and to reconstruction in each condition (see Appendix). Because the usual procedure of complex span tasks involves a single presentation of each memory list, we are particularly interested in the percentages of recall supported by direct access and reconstruction during the first *ST* cycle (the same information is accessible for ST_2 and ST_3 in the Appendix). On the first cycle, the proportion of direct access retrieval is D_1 and the proportion of reconstructive retrieval is $(1\text{-}D_1)RJ_1$ (see Box 1). Direct access was responsible for the correct recall of 45 % and 34 % of the presented letters for the low and high *CL* conditions, respectively, while reconstruction accounted for only 4 % and 3 % of recall in these respective conditions (Table 1 in Appendix). In other words, 92 % (i.e., $45/(45 + 4)$ and $34/(34 + 3)$) of the correct recall in both conditions resulted from direct access. Recall from WM is therefore governed by the two retrieval processes, but direct access constitutes the privileged mechanism. This finding is in line with the widespread conception of WM as a buffer maintaining, in view of online processing, a small amount of information in a state of activation allowing its direct and fast access (Baddeley, 1986; Barrouillet & Camos, 2015, 2021; Miller et al., 1960; Newell, 1990), and supports the views of WM functioning as depicted in the multi-component or the TBRS models.

The second goal of this experiment was to explore the impact on retrieval processes of variations in *CL* that are known to affect recall performance in WM tasks. As already observed in many studies, increasing the *CL* of the secondary task led to reduced recall performance. The novelty here is that the application of the dual retrieval model allowed to identify the locus of this effect. The increase in *CL* resulted in a reduction in recollective processes, whereas non-recollective processes were immune to the *CL* manipulation. As it could be expected from the main tenets of the TBRS model or the multicomponent model and its episodic buffer, recollective processes are affected by *CL*, which is a determining factor in maintaining and accessing information in WM.

Before further discussion, the following Experiment 2 aimed at assessing the effect on processes governing retrieval from WM of a factor expected to affect non-recollective processes, namely the associative relatedness of memory items. Because associative relatedness is known to strengthen the traces left by items in LTM, it could be expected that associative relatedness could facilitate the reconstruction of those items that have not been retrieved through direct access. This experiment aimed also at reassessing which is the privileged process in WM retrievals, and at replicating the effect of *CL* on direct access observed in Experiment 1.

7. Experiment 2

Besides re-examining the implementation of the dual-process model of recall to WM and exploring the impact of *CL* on retrieval processes, Experiment 2 aimed at manipulating the strength of LTM traces to explore its impact of non-recollective processes. Hence, Experiment 2 implemented the same successive *ST* cycles paradigm and *CL* manipulation as in Experiment 1, but introduced a manipulation of the associative relatedness of memory words. It has already been reported that associatively related word lists are better recalled than lists of unrelated words in complex span tasks (e.g., Rosselet-Jordan et al., 2022). To verify that this effect is due to stronger LTM traces for related than unrelated word lists, the present experiment involved two delayed recall tests that followed the complex span tasks after 10 min and 7 days. A better delayed recall of words pertaining to related lists was expected. Although Experiment 1 showed the predominance of recollective direct-access process in WM retrieval, we expected that the better immediate recall of associatively related words would be due to a higher contribution of reconstructive retrieval processes for the related word lists compared to the unrelated word lists.

7.1. Method

7.1.1. Participants

Sixty undergraduate students from the University of Fribourg participated (51 females and 9 males, $M_{\text{age}} = 20.9$ years, $SD = 1.97$). They were randomly assigned to one of the two conditions of associative relatedness. Although we targeted for each group the same sample size as the previous experiment, the signing up procedure led to register 10 additional participants. They received course credits for participating, and none of them took part to the pre-test of the material or the previous experiment.

7.1.2. Material

Twenty-six lists of six associatively related words were created using the French verbal association norms of two databases from De La Haye (2003) and Duscherer et al. (2009). The associative relatedness strength of these lists was pretested by 10 participants who were asked to rate each list on a scale from 1 (unrelated) to 7 (highly related). The 12 best-rated lists were selected for the experiment. Twelve other unrelated-word lists were created by randomly selecting 72 words from De La Haye (2003) and Duscherer et al. (2009). The selected words have a frequency ranging from 31.79 to 61.82 on New et al. (2001) database, and a Bayesian *t*-test provided substantial evidence against a difference in terms of word frequency between related ($M = 44.7$, $SD = 9.46$) and unrelated word lists ($M = 44.8$, $SD = 2.76$, $BF_{10} = 0.29$). These words had one to three syllables, with 76 % of nouns (46 % of them being feminine in French) and 24 % of verbs, each list containing between zero to two verbs.

The associative relatedness strength of the 24 lists (12 related and 12 unrelated word lists) was pre-tested again by 50 participants (39 females and 11 males, $M_{age} = 29.0$ years, $SD = 9.79$) using the same 7-point scale ranging from unrelated to highly related. A Bayesian t-test provided substantial evidence for a higher relatedness in the related ($M = 6.80$, $SD = 0.49$) than unrelated lists ($M = 1.37$, $SD = 0.87$, $BF_{10} = \infty$). Finally, for the 10-min distraction task performed before the delayed recall task, 64 arithmetic equations of the type 1-digit number × 2-digit number were created.

7.1.3. Procedure

The experiment was programmed using *E*-Prime 2.0 software (Psychology Software Tools Inc. [E-Prime 2.0], 2012). The procedure was the same as in Experiment 1 (Fig. 1), except that half of the participants studied the lists of related words (e.g., *bird, cage, feather, egg, beak,* and *wing*) and the other half the lists of unrelated words (e.g., *soul, cocktail, puppet, outlet, puzzle,* and *week*). As in Experiment 1, for each participant, half of the lists were presented in the high *CL* condition, and the other half in the low *CL* condition. After completing the three successive *ST* trials for the 12 lists of words, participants were asked to solve as many arithmetic equations as possible in 10 min. This distraction task aimed at removing the content of WM. Afterwards, without any preliminary warnings, participants were asked to write down as many words as they can remember without taking into account their order of presentation. They had to search for items at least for 5 min, but without no time limit to finish the task. Finally, the same delayed recall task was performed after 7 days. It was conducted online through Qualtrics XM Platform software (2005). Participants received instructions to dedicate at least 5 to 10 min to this test, for which they received an additional course credit.

7.2. Results

Mean and SD for each dependent variable are available on Table 1, and Table 2 shows the $BF_{\text{inclusion}}$ values for the main and interaction effects. In the complex span task, participants complied very well with the instructions of the secondary task (i.e., to read digits aloud) in which there was nearly no errors ($M = 0.52$ %, $SD = 0.56$). In the distracting task before the long-term recall test, participants performed 60.7 % ($SD = 25.0$) and correctly solved 51.8 % ($SD = 24.9$) of the 64 arithmetic problems, corresponding to a rate of success of 84 %.

7.2.1. Recall performance in the immediate recall test

A Bayesian ANOVA with default values with *CL* and trial as within-subject factors, and associative relatedness as between-subject factor was performed on the percentage of words recalled in correct serial position. The best model, $BF_{10} = 1.33 \times 10^{47}$, included the main effects of *CL*, trial, and relatedness, as well as the interaction between trial and relatedness. However, the BFs_{10} of the four best models were rather similar from each other ($BF_{10} = 1.16 \times 10^{47}$, $BF_{10} = 7.43 \times 10^{46}$, and $BF_{10} = 7.12 \times 10^{46}$ for the second, third and fourth model). Compared to the best model, the other models included additional interactions: the *CL* × trial interaction for the second model, the *CL* × relatedness interaction for the third model, and these two interactions for the fourth model. To depart between the models, the $BF_{\text{inclusion}}$ of each effect was examined (Table 2). As in Experiment 1, recall was higher with low ($M = 78.9$ %, $SD = 14.6$) than high *CL* ($M = 74.9$ %, $SD = 16.8$), and increased across trials ($M = 55.0$ %, $SD = 20.7$; $M = 83.1$ %, $SD = 17.0$; and $M = 92.7$ %, $SD = 11.9$ for first, second and third trials, respectively). Although the $BF_{\text{inclusion}}$ for the relatedness effect was inconclusive, descriptively the related words ($M = 81.0$ %, $SD = 11.0$) were better recalled than unrelated words ($M = 72.8$ %, $SD = 17.9$).

Finally, to examine the relatedness × trial interaction, a series of Bayesian *t*-tests was performed comparing in each trial recall performance between the two groups of participants who studied either the related or unrelated lists. As expected, relatedness impacted recall performance in the first trial ($M = 62.4$ %, $SD = 16.4$, and $M = 47.6$ %, $SD = 22.1$ for the related and unrelated conditions, respectively), $BF_{10} = 8.67$, but its effect vanished across the second ($M = 86.9$ %, $SD = 11.8$, and $M = 79.2$ %, $SD = 20.5$, respectively), and third trials ($M = 93.8$ %, $SD = 7.0$, and $M = 91.6$ %, $SD = 15.4$, respectively), $BF_{10} = 1.00$, and 0.32, respectively.

7.2.2. Recall performance in the 10-min delayed recall test

A Bayesian ANOVA with *CL* as within-subject factor and associative relatedness as between-subject factor on the percentage of words correctly recalled indicated that the best model included only the main effect of relatedness, $BF_{10} = 1.37 \times 10^7$. Indeed, related words were better recalled than unrelated ones ($M = 31.7$ %, $SD = 7.8$ and $M = 18.0$ %, $SD = 6.7$, respectively). The second-best model, which added the *CL* effect was 4 times less able to account for the data, $BF_{10} = 3.29 \times 10^6$, which is at odds with our expectation of a *CL* effect on long-term recall.

7.2.3. Recall performance in the 7-day delayed recall test

A similar Bayesian ANOVA was computed on the percentage of words correctly recalled in the delayed recall test performed after a 7-day delay. One participant in the group with related word lists did not reply to this test. Hence, the analysis was run on the data of 59 participants. It yielded similar findings to the previous delayed recall test. The best model included only the relatedness effect, $BF_{10} = 4.96 \times 10^6$, related words being drastically better recalled than unrelated words ($M = 21.0$ %, $SD = 9.1$ and $M = 7.3$ %, $SD = 5.2$, respectively). The second-best model, which included the two main effects, was less able to account for the data, $BF_{10} = 1.35 \times 10^6$.

7.2.4. Model fit and parameter estimations and comparisons

The same analyses as in Experiment 1 were performed to assess the fit between the alternative error model and the data and estimate the model parameters. Model fit was satisfactory, with PPP > 0.311 for all T_1 and T_2 statistics. Population-level parameter estimates are given in Table 4. As in Experiment 1, the majority of the recalled items were retrieved through direct access for unrelated and related word lists (D_1 and D_2 values ranged from 36 to 74 % depending on trial, *CL* and associative relatedness conditions). Reconstruction accounted for 46 to 55 % of the remaining retrievals.

Difference scores obtained either by subtracting the posterior samples of the high *CL* condition from the low *CL* condition (i.e., difference low *CL* – high *CL*) or by subtracting the posterior samples of the unrelated condition from the related condition (i.e., difference related – unrelated) are presented in Table 5.

As in Experiment 1, the only credible difference that emerged were in the D_1 parameter (i.e., direct access after the first trial). There was a main effect of *CL* on D_1, which was higher in the low *CL* than in the high *CL* condition (mean difference = 0.06, 95 %CI [0.000, 0.116]). As shown in Table 5, the *CL* difference on D_1 was only credible for unrelated words, and not for related words. There was also a main effect of relatedness on D_1, which was higher for related than unrelated word lists (mean difference = 0.18, 95 %CI [0.059, 0.283]). The relatedness difference on D_1 was credible in the high *CL*, but not in the low *CL* condition. Contrary to our predictions, there was no credible difference as a function of word list relatedness on the reconstruction parameter, *R* (mean difference = −0.07, 95 %CI [−0.564, 0.513]).

7.3. Discussion

Experiment 2 replicated the three main findings of Experiment 1. First, the trichotomous model provided a particularly good fit of the recall data of our complex span task. Second, although both recollective (ranging from 36 % to 59 % of recall of the presented letters, see Table 2 in Appendix) and non-recollective processes (from 2 % to 6 %) are involved in WM recall, direct access was the privileged process supporting WM retrievals, representing between 85 % and 95 % of the correct recall. Third, the increased *CL* of the secondary task resulted in a decrease in immediate recall performance, which was due to a decrease in direct access to the verbatim traces of studied items, while reconstruction was not affected. The introduction of different memory lists varying in their associative relatedness proved to be efficient, as immediate as well as delayed recall (after 10 min or 7 days) were better for related than unrelated word lists.

Contrary to our expectations, the beneficial effect of associative relatedness on recall did not result from more frequent reconstructions, but from more direct access. This facilitation of direct access to WM traces suggests that associative relatedness does not help to redintegrate degraded memory traces, but affects the encoding of memory traces in the episodic loop in WM. In a last experiment, we implemented another manipulation known to strengthen LTM traces by spacing the presentation of the memory items. Our original prediction was that any strengthening of LTM traces in a WM task would affect reconstruction. The findings of Experiment 2 spoke differently. If the spaced presentation of memory items has similar effects as the associative relatedness, one can expect that spacing the presentation of memory lists would favor recollective rather than reconstructive processes. However, although the associative relatedness between words favored direct access to verbatim traces in the present experiment, spaced presentation of items to be remembered is more likely to promote gist retrieval through reconstructive processes, due to forgetting of verbatim details over time. Experiment 3 aimed at disentangling between the two hypotheses.

8. Experiment 3

In this experiment, each list was no longer presented in three successive *ST* cycles (S_1T_1, S_2T_2, S_3T_3). Instead, there were three blocks of *ST* cycles with all the lists presented in each block. In other words, all the lists were presented in a first S_1T_1 cycle, then a second time in an S_2T_2 cycle and finally in an S_3T_3 cycle. Hence, a word list was no longer studied three times in a row as in Experiment 1 or 2, but its successive presentations were spaced by the study of all the other lists. This spaced presentation of the memory items that is known to strengthen LTM traces should lead to lower immediate recall performance than in the previous experiments, but to better delayed recall than in Experiment 2. Concerning the retrieval processes, it remained open whether the spaced presentation would affect either direct access as the associative relatedness did, or reconstruction due to forgetting of verbatim details and reliance on gist representations. Finally, Experiment 3 aimed at replicating the results of the previous experiments related with the effects of *CL* and associative relatedness on retrieval processes.

8.1. Method

8.1.1. Participants

Sixty students from the University of Fribourg participated in this final experiment (51 females and 9 males, $M_{\text{age}} = 21.5$ years, $SD = 2.27$) and did not participate in any other experiments of this study. They were randomly assigned to one of the two conditions of associative relatedness. The sample size was identical to the previous experiment.

8.1.2. Material and procedure

The same material as in Experiment 2 was used. The procedure was similar to that of Experiment 2, except that, instead of studying the lists in three immediately successive *ST* cycles per list, participants performed an initial *ST* cycle for the entire set of lists (S_1T_1) before moving on to a second (S_2T_2) and third *ST* (S_3T_3) cycle of the entire set of lists. Within each *ST* cycle, the lists were presented in a different random order, which also differed between participants.

8.2. Results

As for the previous experiments, Tables 1 and 2 display the mean and *SD* for each dependent variable and $\text{BF}_{\text{inclusion}}$ values for each main and interaction effects, respectively. Participants complied well with the instructions both for the secondary task in the complex span task in which they did nearly no errors ($M < 1$ %, $SD = 0.37$), and for the distracting task before the long-term recall. In this latter task, participants performed 61.3 % ($SD = 22.6$) of the 64 arithmetic problems, and 52.8 % ($SD = 21.4$) were correct (i.e., 87 % of correct responses on the performed problems).

8.2.1. Recall performance in the immediate recall test

As in Experiment 2, a Bayesian ANOVA with *CL* and trial as within-subject factors, and associative relatedness as between-subject factor was performed on the percentage of words correctly recalled in correct serial position. The best model included the three main effects, $\text{BF}_{10} = 1.54 \times 10^{49}$. It accounted for the data 2.7 times better than the second-best model, which included the three main effect and the *CL* × relatedness interaction, $\text{BF}_{10} = 5.62 \times 10^{48}$. The examination of the $\text{BF}_{\text{inclusion}}$ for the different effects (Table 2) showed that they were smaller than 1 for all the interactions. The *CL* impacted recall with better recall in the low than the high *CL* ($M = 73.0$ %, $SD = 15.8$, and $M = 67.5$ %, $SD = 17.7$, respectively). As previously reported, recall performance increased across trials ($M = 52.9$ %, $SD = 17.6$, $M = 72.9$ %, $SD = 18.3$ and $M = 85.0$ %, $SD = 16.2$ for first, second and third trials). Finally, the related-word lists ($M = 79.1$ %, $SD = 10.5$) were better recalled than the unrelated word lists ($M = 61.4$ %, $SD = 16.2$).

To test our predictions, we performed another ANOVA with the same within- and between-subject factors but contrasting Experiment 2 and 3 as a between-subject factor. The 9 best models did not strongly vary from each other in accounting for the data, with BFs_{10} ranging between

1.22×10^{99} and 3.27×10^{98}. Among them, the model including only the four main effects and the trial × relatedness and trial × experiment interactions was the most parsimonious, $BF_{10} = 5.52 \times 10^{98}$. Moreover, this model included all the effects for which the $BF_{inclusion}$ was higher than 3. Beyond confirming the impact on recall of *CL*, $BF_{inclusion} = 6.41 \times 10^6$, relatedness, $BF_{inclusion} = 4.44 \times 10^3$, and trials, $BF_{inclusion} = 6.15 \times 10^{84}$, this analysis revealed that performance was higher in Experiment 2 (*M* = 76.9 %, *SD* = 15.3) than in Experiment 3 (*M* = 70.3 %, *SD* = 16.3), $BF_{inclusion} = 3.76$. Evidence was gathered for the trial × relatedness interaction as in Experiment 2. Despite the fact that this interaction was not in the best model for Experiment 3, this analysis did not provide support for a trial × relatedness × experiment interaction. Finally, and as expected, the learning effect across trials was stronger in Experiment 2 than in Experiment 3 (an increase of 37.8 % vs. 32.0 % from trial 1 to trial 3, respectively), as testified by the trial × experiment interaction, $BF_{inclusion} = 65.2$.

8.2.2. *Recall performance in the 10-min delayed recall test*

A similar Bayesian ANOVA as in Experiment 2 with *CL* as within-subject factor and relatedness as between-subject factor was performed on the percentage of words correctly recalled after a delay of 10-min filled by a distracting task. It replicated the results of Experiment 2. The best model included only the main effect of relatedness, $BF_{10} = 1.13 \times 10^5$, the second-best model that included the two main effects providing a poorer account of the data, $BF_{10} = 2.17 \times 10^4$. As we expected, related words were better recalled than unrelated ones (respectively *M* = 83.7 %, *SD* = 11.1 and *M* = 56.9 %, *SD* = 21.3).

The comparison with Experiment 2 through another Bayesian ANOVA showed that the best model included the main effects of experiments and relatedness as well as the interaction between these two factors, $BF_{10} = 2.52 \times 10^{36}$. The second-best model, which did not include this interaction, had a much lower BF_{10}, $BF_{10} = 3.99 \times 10^{35}$, and the $BF_{inclusion}$ for the interaction was substantial, $BF_{inclusion} = 6.22$. As expected, recall performance was higher in Experiment 3 (*M* = 70.3 %, *SD* = 21.6) than in Experiment 2 (*M* = 24.9 %, *SD* = 10.0), $BF_{inclusion} = 1.45 \times 10^{33}$. As we already mentioned, related word lists led to better recall than unrelated word lists, $BF_{inclusion} = 2.44 \times 10^{10}$. Finally, the beneficial impact of the related word lists was larger in Experiment 3 than in Experiment 2 (an advantage of 26.8 % and 13.7 %, respectively).

8.2.3. *Recall performance in the 7-day delayed recall test*

One participant in the group with the related word lists and two participants in the group with unrelated word lists did not reply to this recall test. Hence, the analysis was performed on 57 participants. The same Bayesian ANOVA as in the previous delayed recall test was performed on the percentage of correct recall. It highlighted the same best model with only the main effect of relatedness, $BF_{10} = 2.59 \times 10^6$. The second-best model with the two main effects had a smaller BF_{10}, $BF_{10} = 8.76 \times 10^5$. As in the previous analysis, related words (*M* = 62.6 %, *SD* = 17.3) were better recalled than unrelated ones (*M* = 29.7 %, *SD* = 18.1).

When comparing with Experiment 2, a similar pattern appeared, with the best model including the main effect of experiments, relatedness, and their interaction, $BF_{10} = 2.11 \times 10^{26}$. The second-best model additionally included the *CL* effect but had a smaller BF_{10}, $BF_{10} = 3.86 \times 10^{25}$. Moreover, the $BF_{inclusion}$ of the CL effect was smaller than 1, $BF_{inclusion} = 0.18$. Recall performance was higher in Experiment 3 (*M* = 46.4 %, *SD* = 24.1) than in Experiment 2 (*M* = 14.0 %, *SD* = 10.1), $BF_{inclusion} = 8.41 \times 10^{18}$, and for the related than unrelated word lists, $BF_{inclusion} = 2.17 \times 10^{11}$. Finally, the relatedness effect was larger in Experiment 3 than in Experiment 2 (an advantage of 32.9 % and 11.9 %, respectively), $BF_{inclusion} = 1.06 \times 10^2$.

8.2.4. *Model fit and parameter estimations and comparisons*

The same analyses as in the previous experiments were performed to assess the fit between the alternative error model and the data and estimate the model parameters. Model fit was satisfactory, with PPP > 0.086 for all T_1 and T_2 statistics. Population-level parameter estimates are presented in Table 4 and difference scores in Table 5. As in the previous experiments, the recalled items were mostly retrieved by direct access for the related word lists (D_1 and D_2 values ranged from 48 to 59 % depending on trial and *CL* conditions). Reconstruction accounted for 76 to 84 % of the remaining retrievals. This trend was not the same for the unrelated word lists for which D_1 and D_2 parameters were lower (ranged from 12 to 22 % across the conditions) as well as the *R* parameters (around 45–46 %).

Unlike previous experiments, the parameter comparisons showed no credible *CL* differences in any parameter. However, there were main effects of relatedness on the D_1 (mean difference = 0.37, 95 %CI [0.250, 0.481]) and D_2 (mean difference = 0.45, 95 %CI [0.150, 0.667]) direct access parameters as well as in the reconstructive parameter, *R* (mean difference = 0.31, 95 %CI [0.050, 0.536]), which were higher for related than for unrelated word lists. As can be seen in Table 5, credible differences between related and unrelated word lists in D_1 appeared regardless of *CL*. Regarding D_2, the relatedness effect appeared only in the high *CL* condition. For the *R* parameter, the relatedness effect appeared only in the low *CL* condition.

In contrast, the familiarity judgments J_1 and J_2 were higher for unrelated than for related word lists (mean difference = −0.37, 95 %CI [−0.568, −0.165], mean difference = −0.35, 95 %CI [−0.554, −0.085], respectively). This reverse relatedness effect was present only in the low *CL* condition for the J_1 parameter and in the high *CL* condition for the J_2 parameter.

Finally, to test our alternative predictions about changes in recollective processes between Experiments 2 and 3, we computed difference scores comparing the memory parameters of the two experiments by subtracting the posterior samples of Experiment 2 from those of Experiment 3, first by aggregating across conditions, and then by word-list relatedness. There were credible experiment differences in the recollective parameters D_1 and D_2 as well as in the familiarity judgment parameter J_1. Parameters D_1 and D_2 were higher in Experiment 2 than Experiment 3 in which the learning of lists was spaced (mean difference = −0.17, 95 %CI [−0.165, −0.062], mean difference = −0.39, 95 %CI [−0.697, −0.195], respectively). In contrast, the J_1 parameter was higher in Experiment 3 than 2 (mean difference = 0.29, 95 %CI [0.058, 0.471]). When comparing the experiments by word list relatedness, the decrease in parameters D_1 and D_2 appeared only for the unrelated lists (mean difference = −0.27, 95 %CI [−0.403, −0.118], mean difference = −0.52, 95 %CI [−0.708, −0.266], respectively). There was also an increase in the J_1 and J_2 parameters in Experiment 3 compared to Experiment 2, which was only present in the unrelated lists (mean difference = 0.50, 95 %CI [0.260, 0.678], mean difference = 0.31, 95 %CI [0.025, 0.570], respectively).

8.3. *Discussion*

First, it should be noted that findings in Experiment 3 were congruent with the two previous experiments. Although this experiment departed from the usual procedure with three successive *ST* cycles, the statistical fit provided by the dual-process model remained satisfactory, strengthening the applicability of this model to WM recall. Both recollective and non-recollective processes were involved in WM retrieval, and direct access remained the privileged retrieval process, but only for related lists (48 % and 55 % of direct access for low and high *CL* conditions, respectively, compared with 12 % in both *CL* conditions for reconstructions, see Table 3 in Appendix). Hence, direct access accounted for 80 % and 82 % of the correct recall in low and high *CL* conditions, respectively. It should be noted that the percentage of recall supported by direct access in ST_1 cycle was lower for the unrelated lists (15 % and 18 %, compared with 30 % and 20 % for reconstructions in low and high *CL* conditions, respectively). These lower percentages of direct access can be explained by the procedure of Experiment 3 in

Table 3

Summary of the predictions on recall performance and main results.

Predictions	Experiment 1	Experiment 2		Experiment 3	
	Immediate Recall	Immediate Recall	Delayed Recall	Immediate Recall	Delayed Recall
CL effect Lower recall at high CL	✓	✓	×	✓	×
AR effect Better recall with related lists		✓	✓	✓	✓
In Spaced presentation, lower IR and better DR				✓	✓

Note: *CL* for cognitive load, *AR* for associative relatedness, IR for immediate recall and DR for delayed recall. For the sake of simplicity, the findings for the two delayed recall tests in Experiments 2 and 3 were merged in the table as they were similar.

which the three *ST* cycles were not presented in immediate succession.[4] Second, contrary to the two previous experiments, increasing *CL* did not substantially impact direct access, although it had the expected effect on immediate recall performance. Moreover, in contrast to the presentation of associatively related word lists in Experiment 2, the spaced presentation of the lists significantly reduced direct access, resulting in an increased reliance on reconstructive processes. Finally, and importantly for testing the putative effect of strengthening LTM traces on WM retrieval processes, spacing the presentation of the memory lists led to the expected improvement in the two delayed recall tests. We will address the implications of these different findings in the general discussion.

9. General discussion

This study was the first attempt to apply the model of the trichotomous theory to WM for assessing the role of direct access and reconstruction in complex span tasks. It also aimed at examining the impact on these retrieval processes of factors known for affecting the strength of WM traces, i.e., *CL*, or of LTM traces, i.e., associative relatedness between memory items and spaced presentation of memory lists. The three experiments yielded six main findings of fundamental importance to understanding the nature of WM retrieval processes (Table 6). First, the trichotomous model fits recall performance in complex span tasks very well, extending the applicability of this model to WM. Second, it confirms that both recollective and non-recollective processes operate during retrieval from WM. Third, the model indicates that most of the recalled items in WM span tasks are retrieved through direct access, and not reconstructive processes. Fourth, increasing the *CL* of the secondary task, which is known to impair immediate recall performance in complex span tasks, reduces direct access while leaving reconstruction unaffected. The fifth main finding concerns the effect of associative relatedness in increasing direct access. Finally, spacing the list presentation reduces the use of direct access, resulting in a greater reliance on reconstruction processes. These findings have major implications for WM theories, in particular (1) on the role of direct access and reconstruction in immediate serial recall, and (2) on the relationships between WM and LTM. These two points are discussed in turn below.

9.1. Dual processes in WM recall

Table 4

Population-level parameter estimates [95 % credible intervals] of the alternative error dual retrieval model as a function of *CL* (low vs. high) and associative relatedness (related vs. unrelated) in Experiments 1, 2 and 3.

Experiment	Parameters	Low Cognitive Load		High Cognitive Load	
Exp.1	*D1*	0.45 [0.351, 0.549]		0.34 [0.257, 0.426]	
	D2	0.70 [0.505, 0.833]		0.62 [0.375, 0.833]	
	R	0.60 [0.206, 0.985]		0.25 [0.072, 0.622]	
	J1	0.12 [0.042, 0.311]		0.19 [0.039, 0.479]	
	J2	0.19 [0.028, 0.581]		0.53 [0.191, 0.835]	
	J3	0.63 [0.245, 0.945]		0.56 [0.069, 0.920]	
		Unrelated	Related	Unrelated	Related
Exp.2	*D1*	0.47 [0.349, 0.577]	0.59 [0.440, 0.686]	0.36 [0.245, 0.472]	0.58 [0.493, 0.665]
	D2	0.74 [0.524, 0.864]	0.68 [0.506, 0.836]	0.55 [0.201, 0.760]	0.73 [0.552, 0.858]
	R	0.47 [0.098, 0.954]	0.49 [0.114, 0.963]	0.55 [0.240, 0.920]	0.46 [0.095, 0.956]
	J1	0.09 [0.026, 0.260]	0.24 [0.050, 0.616]	0.18 [0.048, 0.414]	0.21 [0.057, 0.573]
	J2	0.26 [0.040, 0.665]	0.61 [0.207, 0.939]	0.40 [0.128, 0.747]	0.26 [0.054, 0.647]
	J3	0.65 [0.120, 0.980]	0.42 [0.020, 0.913]	0.75 [0.251, 0.983]	0.50 [0.095, 0.956]
Exp.3	*D1*	0.15 [0.018, 0.303]	0.55 [0.429, 0.650]	0.18 [0.075, 0.280]	0.48 [0.392, 0.551]
	D2	0.22 [0.022, 0.458]	0.55 [0.104, 0.813]	0.12 [0.006, 0.309]	0.59 [0.334, 0.748]
	R	0.46 [0.315, 0.592]	0.84 [0.567, 0.995]	0.45 [0.339, 0.562]	0.76 [0.451, 0.992]
	J1	0.78 [0.602, 0.955]	0.32 [0.168, 0.546]	0.55 [0.368, 0.767]	0.31 [0.188, 0.531]
	J2	0.71 [0.510, 0.847]	0.49 [0.259, 0.744]	0.67 [0.499, 0.805]	0.30 [0.125, 0.584]
	J3	0.80 [0.600, 0.924]	0.76 [0.367, 0.958]	0.83 [0.645, 0.942]	0.63 [0.314, 0.873]

Note. D_1 refers to the probability that a verbatim trace of an item can be accessed after the first study cycle. D_2 refers to the probability that a verbatim trace of an item that was not accessed in the previous study cycles will be accessed after the current study cycle. *R* refers to the probability that an item whose verbatim trace could not be accessed be reconstructed. J_1 refers to the probability that an item that is reconstructed after the first study cycle is judged to be familiar enough to output. J_2 and J_3 refer to the probability that an item that is reconstructed after the second or the third study cycle, respectively, is judged to be familiar enough to output.

The hypothesis that recalling items involves two distinct processes, a recollective and reconstructive retrieval processes, has been debated for decades (e.g., Brainerd et al., 1982; Brainerd & Reyna, 2010; Brown et al., 2008; Estes, 1960). Although this distinction has been primarily studied in LTM, a similar debate has emerged in the WM research with the question of differences in information retrieval processes between primary memory and LTM (e.g., Conway & Engle, 1994; Wickens et al., 1981). Primary or working memory has often been equated with the current content of consciousness in which a limited amount of information can be retained and is available for current cognition (Baars & Franklin, 2003; see also Andrade, 2001; Baddeley, 1993, 2000; Barrouillet & Camos, 2015, 2021). In this tradition, WM retrieval is

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[4] In the Trichotomous model, *L* is an absorbing state. Consequently, any item recalled in a given *ST* cycle but not in the following cycle enters *P* state. In Experiment 3, the spacing of the *ST* cycles increased the probability of not recalling an item recalled in the previous cycle. This explains why the percentages of direct access were lower, except for related lists in which the gist provides strong retrieval cues that favors recall in successive *ST* cycles.

Table 5

Difference scores [95 % credible intervals] between the *CL* (low − high) conditions and between the associative relatedness (related − unrelated) conditions in Experiments 1, 2 and 3.

Experiment	Parameters	Difference (Low - High Cognitive Load)	Difference (Related - Unrelated)
Exp.1	*D1*	**0.11 [0.034, 0.188]**	
	D2	0.08 [−0.149, 0.351]	
	R	0.36 [−0.189, 0.83]	
	J1	−0.07 [−0.38, 0.188]	
	J2	−0.34 [−0.722, 0.148]	
	J3	0.07 [−0.504, 0.680]	

		Unrelated	Related	Low Cognitive Load	High Cognitive Load
Exp.2	*D1*	**0.10 [0.015, 0.190]**	0.02 [−0.069, 0.11]	0.12 [−0.056, 0.275]	**0.22 [0.079, 0.367]**
	D2	0.18 [−0.06, 0.526]	0.01 [−0.164, 0.297]	−0.06 [−0.286, 0.218]	0.18 [−0.101, 0.563]
	R	−0.03 [−0.589, 0544]	−0.02 [−0.659, 0.613]	0.02 [−0.640, 0.678]	−0.09 [−0.638, 0.503]
	J1	−0.09 [−0.353, 0.122]	0.04 [−0.364, 0.486]	0.15 [−0.104, 0.529]	0.03 [−0.264, 0.429]
	J2	−0.13 [−0.564, 0,415]	0.28 [−0.302, 0.742]	0.35 [−0.203, 0.784]	−0.14 [−0.563, 0.338]
	J3	−0.12 [−0.697, 0.401]	−0.12 [−0.760, 0.523]	−0.22 [−0.828, 0.493]	−0.25 [−0.741, 0.38]
Exp.3	*D1*	−0.02 [−0.200, 0.135]	0.08 [−0.018, 0.177]	**0.40 [0.223, 0.570]**	**0.30 [0.168, 0.427]**
	D2	0.10 [−0.176, 0.347]	−0,01 [−0.447, 0.308]	0.33 [−0.150, 0.680]	**0.47 [0.171, 0.683]**
	R	0.02 [−0.152, 0.191]	0.09 [−0.299, 0.459]	**0.39 [0.083, 0.617]**	0.30 [−0.019, 0.582]
	J1	0.23 [−0.045, 0.485]	−0.01 [−0.262, 0.250]	**−0.46 [−0.699, −0.184]**	−0.24 [−0.508, 0.050]
	J2	0.06 [−0.170, 0.294]	0.19 [−0.152, 0.490]	−0.22 [−0.497, 0.090]	**−0.37 [−0.605, −0.048]**
	J3	−0.01 [−0.215, 0.193]	0.11 [−0.313, 0.450]	−0.05 [−0.441, 0.240]	−0.20 [−0.536, 0.102]

Note. D_1 refers to the probability that a verbatim trace of an item can be accessed after the first study cycle. D_2 refers to the probability that a verbatim trace of an item that was not accessed in the previous study cycles will be accessed after the current study cycle. *R* refers to the probability that an item whose verbatim trace could not be accessed be reconstructed. J_1 refers to the probability that an item that is reconstructed after the first study cycle is judged to be familiar enough to output. J_2 and J_3 refer to the probability that an item that is reconstructed after the second or the third study cycle, respectively, is judged to be familiar enough to output. Difference scores were obtained either by subtracting the posterior samples of the high *CL* condition from the low *CL* condition (i.e., difference Low *CL* – High *CL*) or by subtracting the posterior samples of the related condition from the unrelated condition (i.e., difference related – unrelated). Bolded difference scores exclude 0 from the 95 % credible interval.

assumed to occur via direct access recollective processes, whereas long-term or secondary memory retrieval is assumed to occur via cue dependent search processes, that are akin to reconstructive ones (e.g., Craik & Levy, 1976; Engle & Kane, 2004; Raaijmakers & Shiffrin, 1981). However, things may not be so simple, and some models assume that at least some of the items recalled in WM tasks are retrieved from LTM through search processes based on familiarity judgments. Hence, these models suggest that more complex interactions between various processes and memory systems support immediate recall (Logie et al., 2021, for review). Using the trichotomous theory of recall, the present study gathered evidence in favor of the involvement of the two retrieval processes in WM recall, direct access and reconstruction, and showed that retrieval from WM goes beyond the exclusive use of direct access. Thus, on the one hand, our findings bring support to WM models that assume the existence of sophisticated search mechanisms from LTM to support recall in WM tasks (e.g., Unsworth & Engle, 2007; Unsworth & Spillers, 2010). In addition to the good fit of the trichotomous model to the data of each experiment, the 95 %CI around the estimates of the reconstructive processes always excluded 0, providing credible evidence that they contribute to recall performance. On the other hand, our results also showed a predominance of direct access in immediate serial recall. This latter result echoes the conclusions of previous studies indicating that WM performance depends primarily on the efficiency of direct access, but not on familiarity (Hedden & Park, 2003; Loaiza et al., 2015; Oberauer, 2005). Thus, although recall from WM is governed by a duality of retrieval processes, direct access seems to be the privileged mode of retrieval from WM. These results are consistent with the conception of WM as a buffer maintaining a small amount of information in a state that allows its direct access (Baddeley, 1986; Barrouillet & Camos, 2015, 2021; Miller et al., 1960; Newell, 1990). Moreover, in the trichotomous model, direct access supports the reinstatement of verbatim memory traces of the surface form of the items. These verbatim traces are quite sensitive to the output interference that accumulates during the course of recall, and become rapidly unavailable as time passes (Barnhardt et al., 2006; Brainerd et al., 2009; Reyna & Mills, 2007). The ephemeral nature of these verbatim representations could explain why WM traces are prone to temporal decay or interference, as several theories of WM assume (e.g., Baddeley & Logie, 1999; Barrouillet & Camos, 2015; Cowan, 1995; Oberauer et al., 2012).

The predominance of direct access over reconstructive processes in the present study might be considered surprising, as the ideal conditions were present for eliciting and assessing reconstructive processes, particularly due to the use of a dual task such as the complex span task. According to Unsworth and Engle (2007), memory traces are displaced from primary to secondary memory, from which they are retrieved at recall through a search process, in two occasions. First, the displacement would occur when primary memory is overloaded, for example when the number of memory items in simple span tasks exceeds the size of the primary memory (estimated at 4 chunks). Second, it would also occur when a secondary task requires that distractors are temporally stored in primary memory for their processing. The complex span tasks with interspersed episodes of secondary task between the presentation of memory items are typical of this latter case. Hence, the use of a complex span task in the present study would have favored the displacement of memory items in secondary memory and, hence, their retrieval through reconstructive processes. Therefore, it can then be assumed that the reported frequency of non-recollective processes in the present study is an upper estimation of the occurrence of such processes in WM tasks. Thus, the predominance of recollective over reconstructive processes we observed is a strong indication of the major role of direct access on retrieval from WM.

Another finding supporting the view of WM as a buffer from which memory traces are directly retrieved was the impact of *CL* on retrieval processes. According to the TBRS theory (Barrouillet & Camos, 2012, 2015), higher *CL* involves lower recall performance by increasing the proportion of time during which concurrent processing occupies attention, thus preventing refreshing activities to take place. Within the primary-secondary memory framework (Spillers & Unsworth, 2011; Unsworth & Engle, 2007), it could have been supposed that when refreshing is impeded, memory traces tend to fall into secondary memory from which they can be retrieved through non-recollective processes. The predominance of recollective retrieval and its decrease under high *CL* suggests on the contrary that WM performance is a matter

Table 6

Summary of the predictions on the parameter estimates of the alternative error dual retrieval model and main results.

Predictions		Experiment 1	Experiment 2	Experiment 3	Main findings
Main mechanism for WM retrievals	Recollective (direct access)	✓	✓	✓^{1}×	Mostly direct access
	Non-recollective (reconstruction)	×	×	×	
CL effect	In higher *CL*, less recollective and same reconstruction	✓	✓	×	In higher CL, less direct access and no impact on reconstruction
	In higher *CL*, less recollective and more reconstruction	×	×	×	
AR effect	In related word lists, more reconstruction		×	✓^{2}	In related word lists, more direct access and inconsistent effect on reconstruction
Spaced presentation effect	In spaced presentation, more reconstruction			×	In spaced presentation, less direct access and higher familiarity judgment

Note: ^{1} for related word lists and ^{2} for low *CL* condition.

of maintaining verbatim memory traces by refreshing them in their initial form within something like a focus of attention (Cowan, 2005), a zone of direct access (Oberauer, 2002), a primary memory (Unsworth & Engle, 2007) or an episodic buffer (Baddeley, 2000; Barrouillet & Camos, 2015). When information is verbal, an articulatory rehearsal process probably contributes to the reinstatement of the phonological features of these verbatim traces (Abadie & Camos, 2019; Baddeley, 1986; Camos et al., 2009; Loaiza & Camos, 2018; Lucidi et al., 2016). Preventing maintenance activities by increasing the *CL* of the secondary task seems to disrupt direct access to the surface form of items to be remembered. These items could have irrevocably left WM and be forgotten. However, it is also possible that something of those items remains in a fuzzier form, such as meaning. One can envision that remains of these memory traces in episodic LTM can be retrieved by non-recollective processes, for example in recognition tasks (Uittenhove et al., 2019) or in delayed recognition or recall tasks (Abadie et al., 2024; Abadie & Camos, 2019; Camos & Portrat, 2015). Nonetheless, it can be observed that variations of *CL* did not affect the parameter *R* evaluating the reliance on reconstructive processes, suggesting that these traces do no longer belong to WM. In other words, what our results suggest is that direct access seems to be one of the defining features of WM.

9.2. *On the relationships between WM and LTM*

The relationships between WM and LTM has been a long-standing debate in cognitive psychology since the seminal model of Atkinson and Shiffrin (1968). In the present study, two sets of findings shed new light on this debated issue. First, as mentioned in the previous section, at least part of the performance in immediate recall is due to reconstructive processes. These processes would necessarily call on the involvement of LTM in WM tasks to support the reconstruction of memory traces. Second, we manipulated two factors that have been shown to affect the strength of LTM memory traces, the associative relatedness of memory words within the lists (e.g., Brainerd et al., 1999, 2001; Brainerd & Poole, 1997) and the spaced presentation of these lists (e.g., Cepeda et al., 2006). In the present study, both manipulations improved delayed recall performance, providing evidence that they were effective in strengthening memory traces. However, they had opposite effects on immediate recall and on the underlying retrieval processes. While the associative relatedness increased immediate recall and direct access, the spaced presentation reduced them. These contrasted findings shed a new light on the relationships between WM and LTM.

As we noted above, among the different WM models, Unsworth and Engle's (2007) primary-secondary memory model is the one that most clearly introduces LTM-related reconstructive processes as important mechanisms to understand performance in immediate recall tasks. Using a novel way to examine retrieval processes in WM, the present study provides additional evidence supporting these authors' view. Other WM models also suggest that LTM plays a decisive role in immediate recall. In Oberauer's (2002) concentric model, WM is conceived as that part of LTM activated above threshold. Among these items, a subset of about four items is selected as candidates for ongoing cognition and held in a region of direct access. Within this region, one item is selected for processing and constitutes the focus of attention. As its name indicates, the region of direct access contains items that can be retrieved through recollection when needed, for example for recall purpose. By contrast, those items pertaining to the activated part of LTM, but outside the region of direct access, "can be retrieved only indirectly through associations with items in the more central regions" (Oberauer, 2002, p. 420). This indirect retrieval through associative links is not so far from the search processes in secondary memory described by Unsworth and Engle and akin to the reconstructive processes postulated by the trichotomous theory of recall. In a quite similar view, in Cowan's (1995, 1999) embedded processes model, the focus of attention that stores about 4 chunks of information is embedded in a highly activated part of LTM. Within this framework, the content of the focus of attention would be retrieved through direct access and reconstructive processes may use the items highly activated in LTM as candidates for recall. Because these three models explicitly consider WM as the activated part of LTM, it is rather obvious to account for reconstructive processes among these theoretical frameworks.

Contrasting with them, other models like Baddeley (1986), Baddeley, 2000; Baddeley et al., 2021 for an actual review) multicomponent model or Barrouillet and Camos' (2015, 2021) TBRS model assume that WM is a mnemonic system distinct from LTM. Thus, how can reconstructive processes be understood within these frameworks? These two models share the idea that an episodic buffer temporarily stores memory traces from which they are retrieved through direct access for recall. However, in the TBRS model, because functioning is sequential by nature with only one item processed at a time, memory traces of the other items would degrade. To maintain these traces and avoid their loss, an attention-demanding refreshing mechanism could take the form of a reconstruction of the representations (Barrouillet & Camos, 2015). This reconstruction of WM representations might be similar to the redintegration process assumed to underpin cue-based retrieval in cue-driven accounts of immediate retention (e.g.,Hulme et al., 1997; Nairne, 2002). Remains of degraded memory traces would be used as cues for retrieving potentially relevant information in LTM. These traces could be enriched by the adjunction of new features that were not part of the initial encoding, but also polluted by irrelevant information, which would lead to false memory in short term recall (e.g., Atkins & Reuter-Lorenz, 2008). Such a mechanism has been suggested to account for well-known LTM effects on immediate recall (e.g., word frequency, lexicality, concreteness; Baddeley, 2012; Gathercole et al., 2001).

However, some findings are at odds with this latter proposal. When examining how LTM effects affect refreshing speed and efficiency, Camos et al. (2019) reported that word frequency and lexicality did not modulate refreshing itself, while performance in immediate recall was affected by these LTM effects. Similarly, Rosselet-Jordan et al. (2022) showed that associative relatedness of memory words improved immediate and delayed recall, but did not influence refreshing. Focusing on semantic memory errors that are underpinned by reconstructive processes, Abadie and Camos (2019) also showed that these errors appear in immediate recognition tasks but only when the maintenance of information in WM is prevented. These findings led the authors to suggest that LTM supports immediate recall, but probably not by facilitating the reconstruction of memory traces during their maintenance. Reconstructive processes might occur instead at recall, as previously put forward by Hulme and collaborators (Hulme et al., 1997; Nairne, 2002) through the redintegration of degraded traces, the redintegration being facilitated by the existence of strong LTM representations (e.g., for words vs. non-words, or related vs. unrelated words). The influence of LTM, i.e., the pre-existence of associative links between different information, could also facilitate the encoding of this information, which would be maintained as is in WM by an attentional mechanism acting as a scanning process (Rosselet-Jordan et al., 2022; Vergauwe et al., 2014; Vergauwe & Cowan, 2015).

The findings of the present study, using the trichotomous model of the FTT, significantly advance this debate by characterizing the WM retrieval processes that are affected by LTM effects. First, we showed that manipulating associative relatedness of memory words did not affect reconstructive processes in immediate recall, as previously expected, but direct access, lists of related words eliciting more direct access than lists of unrelated words. Second, the spaced presentation of memory lists reduced the use of direct access, thereby increasing the reliance on reconstructive processes and the use of familiarity judgments to retrieve memorized items. Taken together, these results suggest that not all effects that strengthen LTM traces have the same effect on WM retrieval. This finding is groundbreaking because, contrary to what most models of WM postulate, the influence of LTM on WM retrieval is not always driven by the use of reconstructive processes. For example, the present study showed that associative relatedness improves immediate recall by facilitating direct access to memory items. In this case, pre-existing associative links in LTM could have facilitated the encoding of memory items. From the first presented memory words, the content of the episodic buffer or the focus of attention might trigger the activation of associated LTM representations through spreading activation. These activated LTM representations could have then facilitated the encoding of the rest of the memory lists, leading to the better recall of related-word lists without the recourse to reconstructive processes. Accordingly, the effect of associative relatedness on direct access was particularly clear under high *CL*, the encoding of stronger memory traces making them more resistant to the stronger degradation induced by a secondary task with a high *CL*. Hence, LTM effects could impact immediate recall by strengthening the encoding of memory traces, which favor their direct access. But they could also affect immediate recall by disrupting the formation of strong verbatim traces of memory items, thereby increasing the reliance on reconstruction processes during retrieval, as shown by the manipulation of the spaced presentation of memory lists in the present study. For this LTM effect, it can be envisioned that disrupting the encoding of verbatim traces of items promotes the formation of fuzzier, meaning-based gist traces that are more durable. When recalled, these partial traces must be reconstructed, just as the redintegration process is supposed to do.

The use of models that allow the dissociation of retrieval processes, such as the trichotomous model, seems to be essential to advance the knowledge and models of WM. This study brings a coherent and balanced solution to the debate about the influence of LTM on WM by showing that pre-existing knowledge in LTM favors either the encoding of information which increases direct access, or the retrieval through reconstructive processes, rather than influencing the maintenance of WM representations.

10. Conclusion

This study was a first attempt to apply the trichotomous model to immediate recall in WM span tasks. This approach has proved effective in establishing that both recollective and reconstructive processes govern recall from WM, though WM recall is preferentially based on recollective processes. Overall, our results showed that maintenance in WM does not imply constant reconstruction of traces through retrieval of LTM traces. Short-term recalls are rather recollected than achieved through redintegration of LTM traces or retrieval cues searching.

Of course, this finding, as well as those related with the impact of task difficulty (*CL*) and LTM effect on recall processes, require replication and extension to other WM span tasks. Nonetheless, the present results established that the dual process methodology provided by the trichotomous model has the potential to advance our understanding on the complex interactions among memory systems, their structure and functioning. It opens a new avenue of investigations to memory development, aging and impairments.

Author note

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CRediT authorship contribution statement

Fiona Laura Rosselet-Jordan: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Marlène Abadie:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Stéphanie Mariz Elsig:** Data curation. **Pierre Barrouillet:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Valérie Camos:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Data availability

We have shared a link to the data.

Appendix A

Based on the starting vector W and transition matrix M of the alternative error dual retrieval model (see Box 1), it is possible to compute the exact probabilities for a memory item to be in one of the four possible states distinguished by the Trichotomous model. This computation was performed for each *ST* cycle and condition of the three experiments.

Table 1

Probability for a memory item of being in the four possible states according to the alternative-error dual retrieval model as a function of cognitive load (low vs. high) and study-test trial in Experiment 1.

		State of memory trace			
Cognitive Load	Study-Test Trial	*L*	*Pe*	*Pc*	*U*
Low	1	**0.45**	0.29	**0.04**	0.22
	2	**0.81**	0.13	**0.03**	0.03
	3	**0.92**	0.03	**0.05**	0.00
High	1	**0.34**	0.13	**0.03**	0.50
	2	**0.73**	0.06	**0.07**	0.14
	3	**0.85**	0.05	**0.06**	0.04

Note: *L* refers to a perfect recall state through direct retrieval, *Pe* and *Pc* to partial recall states of reconstructed items reaching or not the familiarity criterion and being thus recalled (*Pc*) or not (*Pe*), while *U* refers to a no-recall state. Probabilities of effective recall are in bold.

Table 2

Probability for a memory item of being in the four possible states according to the alternative-error dual retrieval model as a function of cognitive load (low vs. high), level of relatedness of the memory items, and study-test trial in Experiment 2.

			State of memory trace			
Cognitive Load	Relatedness	Study-Test Trial	*L*	*Pe*	*Pc*	*U*
Low	Unrelated	1	**0.47**	0.23	**0.02**	0.28
		2	**0.85**	0.09	**0.03**	0.04
		3	**0.94**	0.02	**0.04**	0.01
	Related	1	**0.59**	0.15	**0.05**	0.21
		2	**0.84**	0.05	**0.08**	0.03
		3	**0.89**	0.06	**0.04**	0.01
High	Unrelated	1	**0.36**	0.29	**0.06**	0.29
		2	**0.68**	0.16	**0.11**	0.06
		3	**0.80**	0.05	**0.14**	0.01
	Related	1	**0.58**	0.15	**0.04**	0.23
		2	**0.86**	0.08	**0.03**	0.03
		3	**0.94**	0.03	**0.03**	0.00

Note: *L* refers to a perfect recall state through direct retrieval, *Pe* and *Pc* to partial recall states of reconstructed items reaching or not the familiarity criterion and being thus recalled (*Pc*) or not (*Pe*), while *U* refers to a no-recall state. Probabilities of effective recall are in bold.

Table 3

Probability for a memory item of being in the four possible states according to the alternative-error dual retrieval model as a function of cognitive load (low vs. high), level of relatedness of the memory items, and study-test trial in Experiment 3.

			State of memory trace			
Cognitive Load	Relatedness	Study-Test Trial	*L*	*Pe*	*Pc*	*U*
Low	Unrelated	1	**0.15**	0.09	**0.30**	0.46
		2	**0.27**	0.16	**0.38**	0.19
		3	**0.35**	0.11	**0.46**	0.08
	Related	1	**0.55**	0.26	**0.12**	0.07
		2	**0.73**	0.13	**0.13**	0.01
		3	**0.81**	0.05	**0.15**	0.00
High	Unrelated	1	**0.18**	0.17	**0.20**	0.45
		2	**0.25**	0.17	**0.35**	0.22
		3	**0.30**	0.10	**0.49**	0.11
	Related	1	**0.48**	0.27	**0.12**	0.12
		2	**0.71**	0.19	**0.08**	0.01
		3	**0.83**	0.06	**0.10**	0.00

Note: *L* refers to a perfect recall state through direct retrieval, *Pe* and *Pc* to partial recall states of reconstructed items reaching or not the familiarity criterion and being thus recalled (*Pc*) or not (*Pe*), while *U* refers to a no-recall state. Probabilities of effective recall are in bold.

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