1 Precise and imprecise memories may fool you: Continuous memory measures
2 uncover different sources of errors in recognition memory

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ABSTRACT

Recognition memory can be faulty. Participants sometimes incorrectly judge unseen stimuli as seen before (false alarms, FAs), or seen stimuli as not seen (misses). However, the sources of these memory errors remain poorly understood. This study combines an identical(old)/similar/new recognition memory task with a memory precision task to explore sources of recognition memory errors. The results demonstrate that while FAs to similar but unseen items are associated with surprisingly high memory precision, incorrect classification of identical items as 'similar' is associated with a marked decline in memory precision. Lastly, incorrect 'new' ratings to both identical and similar items showed most severely decreased memory precision, over and above that seen for other memory misclassifications. These results suggest that misses are due to memory decay processes, while FAs stem from recollection-based interference between stimuli. The findings lay the groundwork to explore specific memory deficits in different populations.

Keywords:

recognition memory, mnemonic similarity task, old/similar/new task, false alarms, misses, continuous memory measures, memory precision, pattern separation, pattern completion, long-term memory

1 Our memory system does not provide a fail-proof record of our experience^{1,2}.
2 It has long been known that our memories are prone to errors especially if during
3 testing we are presented with stimuli that are similar to those we experienced during
4 encoding. Such recognition memory errors are believed to be partially due to
5 interference, for example from irrelevant information^{3,4}. However, decay of memory
6 traces may also play a role in such memory errors⁵.

7 Much research using ‘similar lure’ stimuli (novel stimuli similar to items that
8 have been studied) to identify memory classification errors exists^{3,6–10}. False alarms
9 (FAs), or the incorrect rating of previously unseen items as ‘old’, in recognition
10 memory tests are unsurprisingly most pronounced when presented items are similar
11 lures, but also occur for completely new items^{8,10}. Participants may approach
12 recognition memory tasks involving similar lures with a so called “recall-to-reject” (or
13 “recollection rejection”) strategy^{11,12}. When using this strategy, they search their
14 memory for a specific stimulus, and then compare the outcome of this memory
15 search to the stimulus presented on the screen. If the retrieved stimulus is notably
16 different from the presented one, they will reject the presented item.

17 While recollection therefore often protects from FAs to similar items, such
18 recollection processes have also been suggested to contribute to FAs. The term
19 “phantom recollection”¹³ describes the vivid experience (i.e., recollection) of a
20 memory of a never presented item, possibly due to lure items eliciting strong gist-like
21 remembering. Consistently, retrieval practice, during which participants repeatedly
22 recall an item without being able to study its detailed features again (strengthening
23 primarily gist-based aspects of the memory^{14,15}), has recently been shown to
24 increase FAs alongside an increase in the correct identification of old items^{16,17}. Lee
25 and colleagues showed that the neural reactivation of *category*-level information (i.e.,
26 of gist-based aspects of the memory) during retrieval practice predicted FAs,
27 supporting the view that strong gist-like remembering contributes to these errors. In
28 contrast, the reactivation of (more detailed) *item*-level information predicted correct

1 rejections of similar lures. That is, reactivating details of the memory helped
2 distinguishing similar lure items from previously learned ones. Thus, recollection
3 processes can increase memory classification errors, while, at the same time,
4 strengthening other aspects of a memory.

5 Consistent with the idea that recollection can be involved in FAs, Kim and
6 Yassa⁸ showed that FAs were more frequent to more similar compared to less similar
7 lures. Such increases in similarity possibly lead to the experience of recollection in
8 participants. Moreover, FAs to lure items that were most similar to studied items were
9 associated more frequently with 'remember' (vs. know) judgements as well as with
10 correct source memory judgements¹⁸, both indicative of recollection. These results
11 are in line with the idea that successful recollection processes contribute to correct¹⁹
12 as well as incorrect 'old' judgements. Moreover, these findings also reveal the role of
13 characteristics of the item itself, such as the effect of item similarity on FAs in
14 recognition memory tests.

15 In recognition memory tests, similar lure correct rejection is seen as a proxy
16 for 'pattern separation' processes¹⁰. Pattern separation describes the transformation
17 of similar memory representations into distinct, non-overlapping ones, a process
18 supported by the hippocampus³. Its counterpart, 'pattern completion', transforms
19 incomplete memories into their previous forms, by "filling in the gaps". FAs to similar
20 lures have been suggested to be driven by increased pattern completion
21 processes^{8,20}, although other phenomena such as encoding processes and familiarity
22 may also contribute to FAs^{21–23}.

23 In contrast to FAs, misses, that is, incorrect 'similar' or 'new' responses to old
24 identical items, may be primarily caused by decay mechanisms rather than
25 recollection-based interference. Identifying an old item as 'identical', requires the
26 retrieval of memory details, a process which is believed to be more vulnerable to
27 decay than to interference⁵. However, while the ability of similar lures to produce
28 'false' recognition responses is well documented, the incorrect classification of

1 previously seen items as 'similar' or 'new', rather than 'identical' (i.e., misses) is not
2 well explored. This lack of research is partly due to the typically much lower trial
3 numbers of misses compared to FAs^{8,9,24}, making it difficult to study this type of
4 classification errors.

5 Investigating hypothetical memory decay processes requires the ability to
6 measure in detail how well participants remember different items. Fortunately, recent
7 research has developed tools to systematically investigate the *precision* with which
8 we remember information²⁵⁻²⁹. These methods that were first developed in the
9 working memory literature^{e.g., 30,31} use *continuous* memory precision measures rather
10 than categorical classifications such as 'old', 'similar', or 'new'. In these tasks,
11 participants recreate stimuli in continuous 360-degree stimulus space (e.g., location,
12 orientation, or colour²⁸), providing detailed insights into the quality of their memories.
13 Such tools are extremely useful, especially when investigating conditions that may
14 result in low trial numbers ('new' and 'similar' responses to identical items), as they
15 provide us with a higher sensitivity to examine these trials.

16 Using such continuous measures, previous research has suggested that
17 failures in recollection processes are indeed associated with a rather sharp decline in
18 memory precision²⁵. However, it is unclear how memory precision measures relate to
19 the frequently employed "old/similar/new" recognition memory tasks described
20 above. What is the relationship between the precision with which we remember
21 aspects of a memory, such as its exact location on a circle, and our ability to
22 correctly identify if the exact item has been presented to us before, a similar item, or
23 a completely new one?

24 With regards to old identical items misjudged as 'similar', in principle two
25 different scenarios are possible. In general, being presented with the identical
26 stimulus should provide a powerful retrieval cue (stronger than being presented with
27 a similar item), resulting in the characteristically observed high rate of 'hits', that is
28 the correct identification of identical items as identical, when presented with the exact

1 same stimulus^{3,8,9,32}. If we assume that this is generally true, identical items
2 incorrectly rated as 'similar' should be those with a relatively poor memory trace,
3 evident in lower memory quality. In other words, if misjudgements of identical items
4 as 'similar' are due to poor memory (e.g., memory decay), we would expect to see
5 lower memory precision for these stimuli in a memory precision task.

6 Alternatively, these mistakes could also result if participants are enforcing
7 overly strict judgement criteria to endorse an item as identical/old. For example, if
8 participants believe that they rate "too many" items as 'identical', they may
9 occasionally and even randomly choose to select 'similar' instead of 'identical',
10 because they think it is unlikely that as many items are identical. In this case,
11 memory for these rejected items could be just as precise as memory for correctly
12 identified old items. Thus, it is not clear if memory quality for identical items judged
13 as 'similar' is qualitatively different from that of correctly identified old items.

14 Other gaps in our knowledge of incorrect responses to identical items
15 concern the lack of understanding of *different types of* "misses". Failures to rate
16 identical items may result in old items are rated as 'similar' (similar-miss), or rated as
17 'new' (new-miss). Therefore, in addition to asking whether memory quality for old
18 identical items incorrectly judged as 'similar' is inferior to that of items correctly
19 judged as 'identical', another question regarding these incorrect responses concerns
20 if incorrect 'similar' responses are also qualitatively different from incorrect 'new'
21 responses to old identical items. Are both types of misses associated with the same
22 decline in memory precision, or are incorrect 'new' responses associated with
23 memory traces that are even more degraded than incorrect 'similar' responses?

24 New-misses are most likely due to low familiarity with the stimulus³³. When a
25 recollection threshold²⁵ is not reached, familiarity signals might still be strong enough
26 to reject the 'new' response in favour of a 'similar' response, but signals may be too
27 weak to elicit the correct 'identical' response. If the 'new' option is chosen, however,
28 it may indicate that in addition to a lack of recollection, familiarity signals might also

be too weak. Consequently, one possibility is that similar-misses are due to a reduced precision of the memory trace, while new-misses are accompanied by a complete loss of the memory trace (guessing). If this is true, memory precision for incorrect 'new' responses may not be different from chance precision. Alternatively, 'new' judgments to identical old items may be associated with worse precision than both correct 'identical' and incorrect 'similar' responses, but they may not always reflect complete forgetting. This may be reflected in memory precision that, while worse than if responding 'similar' or 'identical', could still be above chance level.

The current study combines an identical/similar/new judgement task^{3,9,10} with a precision memory test²⁵⁻²⁹ to address several questions about the quality of memories associated with correct and incorrect responses to the identical (old)/similar/new judgment: (1) Do precision measures track memory misclassifications due to recollection processes (i.e., 'identical' responses to similar items)? (2) Are misses associated with reduced memory precision, and does the degree to which precision is diminished differ between incorrect 'similar', and incorrect 'new' responses? (3) What is the relationship between performance in both types of tasks (identical/similar/lure vs. precision)?

Results

The effect of item condition on the probability of condition choice

Before assessing the precision with which participants responded, it was necessary to determine if participants were able to distinguish between identical, similar, and new items in the condition task. For this purpose, the proportion of 'identical', 'similar', and 'new' responses was investigated for the identical, similar, and new conditions. In most cases participants correctly identified whether they had seen the identical item before, whether they had seen a similar item before, or whether an item was new (Figure 1A).

Figure 1. (A) Percentage of 'identical', 'similar' and 'new' responses for all conditions. Each circle represents one subject. The percentages show the typically observed pattern in recognition memory test with similar stimuli. Relatively larger numbers of correct 'identical' and 'new' responses in the identical and new conditions, respectively, were observed alongside a smaller number of correct 'similar' responses in the similar condition, that were accompanied by incorrect 'identical' responses (FAs) to these items. **(B)** Absolute errors for 'identical', 'similar' and 'new' responses for the identical and similar conditions. As can be seen, incorrect 'similar' responses in the identical condition were associated with a notable increase in location-errors, while incorrect 'identical' responses in the similar condition showed no significant increase in location errors. The black lines represent the mean and the darker shaded area the 95% confidence interval. The lighter areas indicate $mean \pm 1 SD$. Figure created via the notBoxPlot function in Matlab. <https://nl.mathworks.com/matlabcentral/fileexchange/26508-notboxplot>

Since the responses are not independent within the conditions (when a participant responds 'identical', they cannot respond 'similar' or 'new' anymore), I investigated differences in proportions of 'identical', 'similar', and 'new' responses

1 across the identical, similar, and new conditions. Three repeated measures ANOVAs
2 with factor condition (identical, similar, and new) were conducted: one for each of the
3 three response types.

4 The proportion of 'identical' responses differed significantly between the three
5 conditions. The main effect of condition, $F(2,74) = 556.303$, $\varepsilon = .796$, $p < .001$, partial
6 eta squared (η_p^2) = .938, indicated that participants were more likely to choose the
7 'identical' response in the identical condition than in both the similar, $t(37) = 15.440$, p
8 $< .001$, and the new condition, $t(37) = 39.582$, $p < .001$. Thus, consistent with
9 predictions, participants were able to identify identical images and distinguish them
10 from the other two conditions. In line with the pattern observed in previous studies^{8,9},
11 there was also a difference between the similar and new conditions with regards to
12 'identical' responses, where participants were more likely to respond 'identical' to
13 similar, than to new items, $t(37) = 16.098$, $p < .001$. In other words, participants more
14 often wrongly answered 'identical' to similar than to completely new items, indicating
15 some residual memory of the item's 'oldness'.

16 Likewise, there was a main effect of condition for 'similar' responses,
17 Sphericity assumption violated, $F(2,74) = 166.450$, $\varepsilon = .616$, $p < .001$, $\eta_p^2 = .818$:
18 Participants were more likely to classify an item as 'similar' in the similar condition
19 than in both the identical, $t(37) = 14.033$, $p < .001$, and the new condition, $t(37) =$
20 13.001 , $p < .001$. Interestingly, there was also a difference between the identical and
21 new conditions with regards to these 'similar' responses, such that participants were
22 more likely to respond 'similar' to identical, than to new items, $t(37) = 2.358$, $p =$
23 $.0238$. This finding again indicates that similar and identical items were more
24 comparable to each other than both these item types were to new items.

25 Lastly, looking at 'new' responses, there was also a main effect of condition,
26 Sphericity assumption violated, $F(2,74) = 1588.622$, $\varepsilon = .538$, $p < .001$, $\eta_p^2 = .977$.
27 'New' responses were more likely in the new condition than the identical condition,
28 $t(37) = 43.185$, $p < .001$, and than in the similar condition, $t(37) = 38.086$, $p < .001$.

1 They were also more common for similar than identical stimuli, $t(37) = 3.894$, $p <$
2 $.001$, indicating that similar items resembled the new items more than identical items
3 did.

4 Thus, together the data indicate that participants successfully distinguished
5 between the conditions, and were able to tell identical, similar, and new items apart.
6 As expected, the identical and similar condition shared more similarities with each
7 other than the identical and new conditions. The new condition again seemed to
8 share more similarities with the similar rather than identical condition. In other words,
9 as expected, similar items seemed to lie “in between” identical and new items.

10

11 **The effect of item condition and response choice on location errors**

12 With the condition data showing the expected results, it was next important to
13 investigate in how far correct and incorrect ‘identical’/‘similar’/‘new’ judgements
14 differed with respect to their memory precision. Memory precision was investigated
15 by looking at absolute errors between the studied and recreated location in degrees
16 (max. error = 180, with lower errors indicating higher memory precision). Since new
17 items were by definition not associated with a correct (previously encoded) location,
18 the current analysis only focuses on items from the identical and similar conditions
19 (see Figure 1B). One participant did not have any ‘similar’ responses to old identical
20 items, and their data was excluded.

21 **Errors for correct and incorrect responses across conditions.** To allow
22 for a direct comparison with performance in the condition task, an analysis of location
23 errors is first conducted for each response type across conditions using t -tests. As
24 expected ‘identical’ responses were associated with smaller errors when they
25 occurred in the identical, than in the similar condition, $t(36) = 2.387$, $p = .022$.
26 Moreover, ‘similar’ responses were associated with smaller errors when they
27 occurred in the similar than in the identical condition, $t(36) = 5.220$, $p < .001$. Lastly,
28 while location errors were numerically smaller for incorrect new responses in the

1 similar than identical condition, this difference was not statistically reliable $t(36) =$
2 1.534, $p = .134$. Thus, the error data tracked condition choice accuracy.

3 Taking advantage of the fact that location errors (in contrast to condition
4 choices) could also be compared *within* conditions in this task, I assessed
5 differences in location errors associated with each response type within each
6 condition. Supporting my hypotheses, I found that errors were smallest (responses
7 most precise) when participants correctly identified the item category, for both
8 identical and for similar items. An ANOVA with factors response ('identical', 'similar',
9 'new') as well as condition (identical vs. similar items) resulted in a main effect of
10 condition with overall more precise responses in the similar condition, $F(1,36) =$
11 14.210, $p < .001$, $\eta_p^2 = .283$, and a main effect of response with overall higher
12 precision for identical responses, Sphericity assumption violated, $F(2,72) = 149.951$,
13 $\varepsilon = .666$, $p < .001$, $\eta_p^2 = .806$. These two main effects were qualified by an
14 interaction, Sphericity assumption violated, $F(2,72) = 5.234$, $\varepsilon = .635$, $p < .0197$, $\eta_p^2 =$
15 .127. Follow-up ANOVAs indicated that there was a main effect of response both for
16 the identical condition, Sphericity assumption violated, $F(2,72) = 79.347$, $\varepsilon = .689$, $p <$
17 .001, $\eta_p^2 = .688$, as well as for the similar condition, Sphericity assumption violated,
18 $F(2,72) = 97.302$, $\varepsilon = .569$, $p < .001$, $\eta_p^2 = .730$. However, subsequent t -tests revealed
19 a different pattern in results between conditions, as described below.

20 In the identical condition, errors were smaller for 'identical' than 'similar'
21 responses, $t(36) = 5.811$, $p < .001$, and smaller for 'identical' than 'new' responses,
22 $t(36) = 12.168$, $p < .000$, and lastly also smaller for 'similar' than 'new' responses,
23 $t(36) = 6.832$, $p < .001$. In the similar condition, in contrast, follow up t -tests revealed
24 that errors were numerically, but not significantly smaller for 'similar' than 'identical'
25 responses, $t(36) = 0.529$, $p = .600$. They were, however, smaller for 'identical' than
26 'new' responses, $t(36) = 10.007$, $p < .001$, and smaller for 'similar' than 'new'
27 responses, $t(36) = 10.158$, $p < .001$. In other words, while items incorrectly judged as
28 'new' were associated with the highest errors in both the identical and similar

1 conditions, an incorrect decision in favour of one of the other two response options
2 led to a significant increase in errors compared to correct responses when the item
3 was indeed identical (incorrect 'similar' response, similar-miss), but not when it was
4 similar (incorrect 'identical' response, FA). Briefly relating these findings to my
5 hypotheses, this relative increase in location errors for similar-misses suggests that
6 these misclassifications in the identical condition might be associated with memory
7 decay processes. In contrast, trials misclassified as 'identical' in the similar condition
8 (FAs) showed relatively low location errors and thus could be due to recollection
9 processes misleading participants to these misclassifications due to a heightened
10 'feeling' of successful remembering.

11 **Incorrect 'new' responses.** As discussed above, with regards to incorrect
12 'new' responses, it is possible that participants retained residual memory traces,
13 even when they judged an identical or similar item to be 'new'. In the current study,
14 incorrect 'new' responses were followed by an average error of 85.05 degrees for
15 identical and 76.09 degrees for similar items. For the identical condition, this error
16 was not significantly different from the error expected if participants randomly
17 guessed the locations (expected error = 90 degrees), $t(36) = 1.111$, $p < .274$. For the
18 similar condition, however, the error was significantly lower than would be expected
19 for guesses, $t(36) = 3.229$, $p = .003$. This last finding suggests that when participants
20 incorrectly judged an item as 'new' in the similar condition, a residual memory trace
21 may have survived, that participants started to remember the location when doing the
22 location task, and/or that they accidentally "pressed the wrong button" in the condition
23 task, perhaps more frequently for similar than identical trials (as similar and new trials
24 possibly resembled each other more than identical and new trials, as mentioned
25 above).

26 Yet, as mentioned before, the difference in location error between incorrect
27 'new' responses in the identical and in the similar condition was not significant. That
28 is, there was a lack of a significant difference in location error *between conditions*,

1 together with a significant difference compared to chance in one (the similar) but not
2 the other (the identical) condition. This inconsistency in effects between the similar
3 and identical condition complicates the interpretation of the location-error data for
4 incorrect 'new' responses.

6 **Relationship between condition response accuracy and location errors**

7 With the goal to directly relate performance in both types of memory
8 assessments, I correlated condition-judgment accuracy and location-error in the
9 precision task with each other across participants. Correctly identifying the item
10 condition was associated with smaller average location errors (Figure 2). This was
11 true for identical items correctly judged as 'identical', $r = -.602$, $p < .001$, and similar
12 items correctly judged as 'similar', $r = -.598$, $p < .001$. In contrast, more frequent
13 incorrect condition choices were associated with higher average errors across
14 participants. This relationship was seen for identical items that were judged as
15 'similar', $r = .366$, $p = .026$, as well as similar items judged to be 'identical', $r = .360$, p
16 $= .026$. Thus, participants that were more exact in their condition judgement, also
17 showed higher precision (lower errors) in response to the location-precision question.
18 In turn, higher rates of imprecise responses were associated with lower precision in
19 the subsequent location task. Lastly, more often incorrectly judging an identical item,
20 $r = .080$, $p = .634$, or similar item, $r = .205$, $p = .216$, as 'new' did not predict
21 subsequent errors in these trials across participants. Therefore, location precision
22 tracked condition accuracy for correct and incorrect 'identical' and 'similar'
23 responses, but not for incorrect 'new' responses.

Figure 2. Correlation between percentage of 'identical', 'similar' and 'new' responses and average error in the identical (top) and similar (bottom) condition across participants. As can be seen, a higher number of correct responses in the condition task correlated with lower errors in the location task, while the opposite was true for incorrect 'similar' or 'identical' responses. No relationship between both tasks was observed when participants incorrectly chose the 'new' response.

Discussion

The current paper employed a memory precision task to investigate the quality of memories associated with correct or incorrect responses in a forced choice 'identical(old)/similar/new' recognition memory task, containing similar lures and novel items alongside old identical ones. The data revealed that any type of misses, compared to correct responses, were associated with reduced memory precision, while, paradoxically, FAs to similar items were associated with high memory precision in a subsequent location-memory precision task.

Consistent with previous research participants were able to distinguish between identical, similar, and new items. However, especially when presented with similar items, they were often misled to indicate that an item was 'identical' instead of 'similar'. These findings are in line with previous studies that showed a larger number of FA-type errors ('identical' responses to similar items) than miss-type errors ('similar' or 'new' responses to identical items)^{3,8-10}.

1 The analysis of the location-error data importantly complemented this picture.
2 While results from the ‘identical(old)/similar/new’ condition task seemed to suggest
3 that participants had most trouble (i.e., worst performance) in the similar condition,
4 the location-error data indicated that this apparent deficit was not associated with a
5 significant decrease in the *precision* of the participants’ memories. Paradoxically,
6 these FA-type errors seem to be due to *stronger* memories overall: a stronger
7 memory signal seems to be driving participants towards the ‘identical’ response, and
8 these trials are consistently associated with overall lower location errors. Thus, FAs
9 are not *only* caused by strong gist-like memories^{13,16}, but highly precise memories
10 also contribute to these types of memory misclassifications. These findings are
11 consistent with the idea that strong recollection signals lead participants to incorrectly
12 endorse similar items as ‘identical’⁸. In other words, these misjudgements seem to be
13 in part driven by *external* memory features, such as the precision with which
14 associated information – in the current study the item’s location – is recalled (see³⁴
15 for related results using contextual stimuli).

16 As noted in the introduction, FAs to similar stimuli have been suggested to be
17 due to abnormal pattern separation and completion processes^{3,5,9}. The current data
18 is notable, in that it suggests that memory traces might not suffer poor quality per se
19 (as may often be the result of poor pattern separation, which could then result in
20 increased susceptibility to errors during pattern completion), but rather, that precise
21 and intact memory traces contribute to FAs by providing a heightened sense of
22 recollection.

23 In addition to this effect of external memory features (location memory), it has
24 been suggested that item-inherent characteristics might play an important role in FAs
25 to similar items⁸: To explore this possibility, I conducted an additional analysis
26 focussing on the ‘saliency’ of the individual items (see supplementary information,
27 SI). When salience of an item was low participants misjudged the item condition even
28 in case of precise memories (Supplementary Figure 1). Thus, the use of memory

1 precision measures provided evidence that *external* information such as location-
2 memory affects condition choice when presented with similar stimuli, but also that
3 *item-inherent* characteristics such as an item's salience does.

4 Most importantly, the current study also provided unprecedented insights into
5 memory misclassification in the identical condition. This data is often not analysed in
6 depth due to low trial numbers in other studies, but by using a memory precision
7 task, the current design provided a novel approach to analyse these errors. While
8 participants had the highest rate of correct responses in the identical condition, those
9 items that were incorrectly judged as 'similar' instead of 'identical' in this condition
10 were associated with a significant decrease in memory precision. That is, in contrast
11 to condition misjudgements as 'identical' in the similar condition, in the identical
12 condition an increase in location errors for misclassifications of items as 'similar' was
13 observed. Misclassifications in this condition were associated with worse memory
14 quality. This increase in location errors was especially apparent if the incorrect
15 response was given to an item that resulted in good memory performance across
16 participants (high saliency, see SI), or simply put, a relatively 'memorable' or 'easy'
17 item. This finding indicates that incorrect 'similar' responses to identical items might
18 be due to memory decay processes in contrast to FA-type errors to similar items.

19 As a whole, the pattern of results observed in this study therefore suggests
20 that condition-misjudgements to identical items might be due to different mechanisms
21 than the FAs to similar items described above. Misjudged identical items appear to
22 be caused by degraded memories, and an overall weaker memory trace, leading
23 participants to incorrectly choose the 'similar' instead of the correct 'identical' option.
24 Thus, in these trials pattern completion might fail due to the poorer quality of the
25 memory trace, rather than interference.

26 In the introduction it was discussed that, when judging identical items as
27 'similar', participants may adapt an *overly* strict criterion, or that they could make
28 strategic, random 'similar' choices when they perceive their overall rate of 'identical'

1 responses to be “too high”. While both options might contribute to performance in the
2 current task, the location error data suggests that misclassification of identical items
3 as ‘similar’ cannot solely be explained by these two options: Decay of the memory
4 traces also seems to play a role. That is, participants might use a strict criterion, but
5 the items that do not pass this criterion are *also* qualitatively different from those that
6 do. Moreover, participants might occasionally strategically call an item ‘similar’ even
7 if they think they have seen the identical one, but they might not choose these items
8 randomly, but based on their quality.

9 With regards to the source of the poor quality of these memories, it should be
10 noted that it is also possible (and likely) that a certain number of items are not
11 remembered precisely because of deficits in the *encoding* stage. Further research
12 might address this issue by including measures like eye-tracking, which allow to
13 monitor encoding processes²².

14 The supplementary saliency analysis revealed that, strikingly, for the possibly
15 most similar/difficult to distinguish items (items with lower saliency), location error
16 was even lower for incorrect ‘identical’ than correct ‘similar’ judgements (see SI).
17 That is, participants showed very precise location memory when they confused these
18 lures with previously seen items. This finding revealed an important interaction
19 between two aspects of memory: characteristics of the items themselves, such as
20 low salience (making items harder to distinguish), as well as strong recollection of
21 associated information, such as highly precise location memory. If participants
22 precisely remember associated aspects of a memory, such as its location, this might
23 bias them to judge an item as ‘identical’, even if it was just similar, especially for
24 items of low saliency. Similarly, a poor memory for the item’s location might drive
25 participants to judge an item as ‘similar’ rather than ‘identical’, even for items leading
26 to good memory performance across participants (i.e., high salience items). Together
27 these findings suggest that identical(old)/similar/new ratings are affected by at least
28 two different characteristics of a memory: the similarity of a probe item and the

1 studied item, as well as the quality of a memory trace containing non-item-inherent
2 information such as the location, potentially subserved by at least partially distinct
3 brain mechanisms^{18,35}.

4 Moreover, the current study also provided some valuable insights into misses
5 to identical and similar items that resulted in a 'new' response. Unsurprisingly, the
6 results indicated that correct 'identical' and 'similar' judgements were associated with
7 lower location errors than incorrect 'new' responses. In addition, the data also
8 revealed a difference in location error between identical and similar items
9 misclassified as 'new', and misclassified as 'similar' and 'identical', respectively. Out
10 of all responses, incorrect 'new' ratings were associated with most severely reduced
11 quality and in the case of the identical condition possibly a complete lack of the
12 memory trace. The high location errors observed in this condition indicate that
13 participants only revert to these 'new' responses when memory traces are severely
14 impaired.

15 Location-errors following an incorrect 'new' choice in the identical condition
16 did not significantly differ from what would be expected when participants guessed
17 the location. For the similar condition, 'new' responses were associated with
18 comparably high location errors, but these errors were still significantly smaller than
19 what would be expected when guessing. This finding indicates that, potentially,
20 location memory traces survived, but were not sufficient to result in a 'similar'
21 response. Of note, in a certain number of trials participants may have simply
22 "pressed the wrong button", and therefore could still provide the correct location
23 afterwards. The wrong button may have been pressed more frequently for the similar
24 condition, which, as mentioned above was more similar to the new condition than
25 identical items. (The similar condition was "in between" the identical and new
26 conditions). However, as there was no significant difference in the location error
27 between 'new' responses in the identical and similar conditions, future research is

1 needed to further investigate the precision of 'new' responses to identical and similar
2 items, ideally using large trial numbers to acquire larger numbers of 'new' errors.

3 Lastly, the correlation analysis directly related performance in both tasks to
4 each other; an important step in comparing studies using either method. The data
5 suggests that participants with more accurate responses in the
6 identical(old)/similar/new task also showed lower location errors than participants
7 with more inaccurate condition choices. While, on the single-trial level, memory
8 precision might differentially influence responses in the condition task as reviewed
9 above, across participants better performance in one task was thus associated with
10 superior performance in the other task. Therefore, both tasks seem to index related
11 processes, and can be used to complement each other.

12 Since identical(old)/similar/new type paradigms have repeatedly been used to
13 study memory impairments for example due to amnesia, Alzheimer's disease, mild
14 cognitive impairment, or healthy aging^{9,10,20,21}, and these memory impairments are
15 also increasingly studied using continuous memory measures³⁶⁻⁴¹, the current data
16 provide a critical first step in linking research in both fields. Future work could directly
17 explore if and how precision and identical(old)/similar/new judgments are affected
18 differentially in these populations, to reveal if we can detect diagnostic impairment
19 patterns. For example, precision in selective subconditions in the
20 identical(old)/similar/new task could be most diagnostic of further memory decline in
21 older adults, or location errors might be affected in different subconditions depending
22 on the exact type of a memory deficit, such as different types of amnesias.

23 To summarize, the data of the current study critically adds to previous
24 research by using a precision memory task to provide insights into different
25 classification mistakes occurring in an identical(old)/similar/new task. While high
26 memory precision contributes to FA type errors to similar items, incorrectly judging
27 identical items as 'similar' is driven by comparably low memory precision. Thus, the
28 use of the memory precision paradigm in the current study allowed for critical new

1 insights into the factors underlying two kinds of mnemonic errors: the
2 misclassification of identical old items as 'similar' and the misclassification of similar
3 items as 'identical'. The combination of both paradigms also offers some first insights
4 into differences in memory precision between incorrect 'new' and incorrect
5 'similar'/'identical' responses, with the earlier being associated with more degraded
6 memories than the later. The combination of both paradigms provides important data
7 aiding the comparison of studies using the well-established old(identical)/similar/lure
8 paradigm and more recently developed continuous memory precision judgments.

1 **Methods**

2 **Participants**

3 The sample included 38 participants (26 females) with a mean age of 20.5
4 years ($SD = 1.90$), recruited from the Leiden University community using the online
5 sign-up system SONA. One additional participant was tested, but aborted the study.
6 Their data was never included in the analyses. All participants had normal or
7 corrected-to-normal vision and were screened for colour-blindness, neurological, and
8 psychiatric disorders using self-report questionnaires. They received payment or
9 course credits for their participation. All participants provided informed consent, and
10 the study was approved by the ethics committee of Leiden University.

11

12 **Materials**

13 The stimulus set for this experiment consisted of 318 pictures. Of these, 18
14 pictures were used in a practice task and 300 in the main experiment. Pictures
15 included common everyday objects that were well known to all participants, and easy
16 to name, such as guitar, handbag, etc. During both the practice and the main
17 experiment, 1/3 of the pictures were part of the *identical* condition. In this condition
18 the exact same picture was presented during a study phase and a subsequent test
19 phase (see Procedure for more details). One third of the images were part of the
20 *similar* condition. In this condition during the test phase a similar, but not identical
21 image to that which had been shown during the study phase was presented to
22 participants (see Figure 3 for examples). The last third of the pictures constituted
23 *new* items, and these pictures were dissimilar to any picture presented previously.
24 The images were presented on a background image of clouds. Participants were
25 also required to learn the location of each item presented on this background
26 (location-precision task, described below).

27

Figure 3. Example stimulus pairs of identical and similar pictures for a (A) letter box and (B) chewing gum. Across participants it was randomised if the identical stimulus to the one previously studied, or a similar lure was shown in the later test phase.

Procedure

All participants filled in a consent form and a demographics questionnaire. They were asked to read the instructions on a PowerPoint presentation and complete a short training task to familiarize themselves with the task demands, including the continuous response options in the location precision task (described below). Participants completed 2 practice blocks. Each block contained a study and a test phase, which are illustrated in Figure 4A and B. The practice session consisted of 12 study and 18 test trials spread across the 2 blocks. Each study block contained 12 pictures and each test block 6 identical, 6 similar, and 6 new pictures. Stimuli used in this training session did not overlap with stimuli used in the main experiment. Stimulus presentation was done using Matlab (Mathworks, Natick, MA) and the Psychtoolbox (www.psychtoolbox.org).

In each study trial participants were presented with a picture that was located in a randomly chosen location on an invisible circle, superimposed on a background image of clouds. The picture was presented for 3 s followed by a 500 ms fixation cross. Participants were instructed to try to memorize the exact pictures and their location on the display as precisely as they could.

(A) Study Phase

(B) Test Phase

Figure 4. (A) In the study phase participants studied pictures. In each trial they were presented with a picture on different locations on an invisible circle on a background image of clouds for 3 s. Pictures were separated by a 500 ms fixation cross (not shown). (B) In the test phase, participants were first presented with an image in the centre of the screen on a black background. They had 3 s to select whether the item was new (never seen before), similar (but not identical) to a previously seen item, or if it was identical to an item seen during the study phase, by selecting one of the three response boxes. Then they were asked to move the picture to the location they remembered having seen it. They had 5 s to complete this location precision task. If participants said the image was new they were instructed to choose a random location.

1 Each test trial consisted of a two-step memory test (see Figure 4B). In the
2 first step, participants were tested to see if they could identify the item
3 (identical/similar/new judgment; condition task). In the second step they were asked
4 to recreate its location (precision task). To test for memory of item identity,
5 participants were presented with an identical, similar, or new item, in the centre of the
6 screen on a black background, and had to select from three response options
7 presented underneath: 'identical', 'similar', or 'new'. The option 'similar' was always
8 presented in the middle, but the assignment of the 'identical' and 'new' options to the
9 left or right was counterbalanced across participants. Participants had 3 s to select
10 their response by using the 'g', 'h', and 'j' keys on a standard computer keyboard.
11 The order of the keys corresponded to the order of the boxes on the screen (i.e., 'g'
12 for identical/new, 'h' for similar and 'j' for new/identical, depending on
13 counterbalancing). To encourage participants to respond a red circle around the
14 image appeared when participants had only 1 s left to make their choice. After
15 responding, the chosen box turned grey for 200 ms to indicate to the participant that
16 the response was recorded before moving on.

17 After a 500 ms fixation cross, participants were presented with the picture at a
18 random position on the invisible circle on the cloud background. The participants
19 were asked to recreate the pictures' previous location using a continuous dial (360
20 increments). If participants thought an item was similar, they were instructed to move
21 it to the location that the corresponding similar items was presented in during the
22 study phase. The word "Location" was presented in the centre of the screen and
23 participants had 5 s to move the item to a circle-location of their choice using the 'g'
24 and 'j' key on the keyboard. They locked their answer using the spacebar. When only
25 1 s was left to respond the word "Location" in the centre of the screen changed
26 colour from white to red, to encourage participants to lock their response. Two
27 hundred ms after pressing the spacebar participants were presented with another
28 500 ms fixation cross, and the task moved on. Participants were instructed to move

1 the item even when they classified an item as 'new', to test if any residual location
2 memory was detectable even if participants did not remember a previously presented
3 item (i.e., in miss trials). The order of the pictures in the study and test blocks was
4 randomized.

5 The task in the main experiment was identical to that in the practice. In the
6 main experiment each participant learned 200 stimuli, and completed the test phase
7 on 300 stimuli. The 300 test stimuli consisted of 100 old identical images, 100 old
8 images that were similar, but not identical to the learned images, and 100 new
9 images. Participants completed 10 blocks of 20 study/30 test trials each. Each block
10 had equal numbers of identical/similar/new items in the test phase.

11

12 **Analysis approach**

13 Data will be analysed focussing on both, performance in the identical
14 (old)/similar/new condition task, as well as on the precision with which participants
15 recreated the location of the items in the second step of the test phase. Repeated
16 measures analyses of variance (ANOVAs) will be used to detect reliable differences
17 between conditions. Where the assumption of Sphericity was violated in these
18 ANOVAs, *p*-values based on the adjusted degrees of freedom according to
19 Greenhouse-Geisser will be reported with original *F*-values and original degrees of
20 freedom, alongside the Greenhouse-Geisser Epsilon value.

21 Performance in the condition task will be analysed by focussing on the
22 proportion of 'identical'/'similar'/'new' responses across conditions. Location precision
23 will be analysed by focussing on the absolute error in the location task (difference
24 between studied location and recreated location in degrees, with high errors
25 indicating low precision).

26

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4 supported by the Leiden University Fund and Elise Mathilde Fund.

5

6 **Data and Code availability**

7 The code and data for all analyses will be made available in due course at
8 <https://github.com/BaMLaboratory>.

9

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Supplementary Information

To analyse how characteristics of the items themselves affect memory precision, an additional analysis was conducted, taking the ‘saliency’ of items into account. Certain items might be more memorable overall and lead to good recognition performance across participants. Such highly ‘salient’ items should rarely evoke incorrect ‘similar’ responses, and might only do so in the case of a severely decayed memory trace.

To test for effects of saliency, saliency scores are computed separately for each participant excluding their own responses to the items (see¹, for a similar approach). Specifically, for each participant and item, the responses that other participants give to an (identical or similar) item are used to determine saliency. Which version of an item (the identical or similar version) is presented to a subject is randomised across participants. Saliency is measured as the number of correct responses to identical and similar items. If participants generally responded correctly to an item it was considered of high saliency, if not, of low saliency. Items were assigned to one of two saliency bins via median split. Figure 1A in the main manuscript shows a low salience, Figure 1B a high salience item.

Of note, using this computation of saliency, saliency is most likely driven by several factors: Items that elicited a high number of incorrect responses in the similar condition could for example be associated with more *similar* lures, resulting in low saliency². Moreover, a lack of overall *memorability* could lead to more incorrect responses when the identical item is presented. In turn, items that were most often correctly identified could have low similarity lures, or be in other ways highly memorable (high saliency).

Results

Effects of item saliency on performance in the condition task

The data set was divided into high and low 'saliency' items based on subject responses as described above. Since this step required trials to be further divided into the two saliency bins, trials with 'new' responses were excluded from the saliency analyses, due to overall low trial numbers which would have resulted in too many empty cells for the already infrequent 'new' responses. As these new responses were excluded, the percentages in Supplementary Figure 1 do not sum to 100%. Using this approach of only analysing 'identical' and 'similar' responses, all but 6 participants could be included in the analysis.

To assess the effect of saliency in the condition task, data were analysed separately for 'identical' and 'similar' responses, to account for the dependency between the responses. First it was assessed whether the number of identical responses varied depending on saliency (high and low) and condition (identical or similar items). This ANOVA for 'identical' responses revealed a main effect of condition, $F(1,31) = 190.954$, $p < .001$, $\eta_p^2 = .860$, as well as a main effect of saliency, $F(1,31) = 48.560$, $p < .001$, $\eta_p^2 = .610$. These main effects were further qualified by an interaction between condition and saliency, $F(1,31) = 113.440$, $p < .001$, $\eta_p^2 = .785$. While there was no significant difference in 'identical' responses between more and less salient items in the identical condition, $t(31) = 1.564$, $p = .128$, less salient items resulted in a larger number of 'identical' responses in the similar condition, $t(31) = 10.471$, $p < .001$. Thus while saliency did not significantly increase correct identification of identical items, lower saliency seemed to lead participants to confuse similar lures and studied items.

(A)

(B)

Supplementary Figure 1. (A) The effect of item saliency (calculated separately for each participant) on the percentage of 'identical' and 'similar' responses in the identical and similar condition. Saliency affects the proportion of 'identical' and 'similar' responses only in the similar, but not in the identical condition. **(B)** The effect of item saliency on location error in the identical and similar condition for 'identical' and 'similar' responses. Saliency affected the size of the location error in the identical condition only for incorrect responses. In the similar condition correct vs. incorrect responses were differentially affected by saliency. The black lines represent the mean and the darker shaded area the 95% confidence interval. The lighter areas indicate $mean \pm 1 SD$. Figure created via the notBoxPlot function in Matlab. <https://nl.mathworks.com/matlabcentral/fileexchange/26508-notboxplot>

For 'similar' responses, the corresponding analysis resulted in main effects of condition, $F(1,31) = 157.194$, $p < .001$, $\eta_p^2 = .835$, and of saliency, $F(1,31) = 88.158$, $\eta_p^2 = 0.740$. Again, the interaction between saliency and condition was significant, $F(1,31) = 92.685$, $p < .001$, $\eta_p^2 = .749$. While there was also no significant differences in 'similar' responses between more and less salient items in the identical condition, $t(31) = 1.1601$, $p = .255$, less salient items resulted in a smaller number of 'similar' responses than more distinct items in the similar condition, $t(31) = 10.217$, $p < .001$. Thus, higher saliency seemed to make it easier to identify that an item was only similar, but not identical. Together, item saliency only affected 'identical' and 'similar' responses in the similar condition, while no such differences were detected in the identical condition.

Effects of item saliency on location errors

To assess if the location-error data could elucidate the relationship between item saliency and memory classifications further, the effect of saliency on the error data was examined. Looking at the visual pattern of location errors first (see Supplementary Figure 1B), here it can be seen that, in contrast to the condition responses, saliency appeared to influence location error in the identical condition. Especially incorrect 'similar' responses to identical items seemed to be affected by saliency.

An ANOVA with factors saliency (high vs. low), response ('identical', 'similar') as well as condition (identical vs. similar items) was conducted on the location error data. This ANOVA resulted in a main effect of condition, $F(1,31) = 14.829$, $p < .001$, $\eta_p^2 = .324$, a main effect of response type, $F(1,31) = 22.517$, $p < .001$, $\eta_p^2 = .421$, and a main effect of saliency, $F(1,31) = 4.593$, $p = .040$, $\eta_p^2 = .129$. Importantly, these effects were qualified by several interactions. There was an interaction between condition and response type, $F(1,31) = 40.302$, $p < .001$, $\eta_p^2 = .565$, which was further qualified by an interaction between condition, response type, and saliency,

$F(1,31) = 22.008$, $p < .001$, $\eta_p^2 = .415$. Separate follow-up ANOVAs for the two conditions revealed a significant interaction between saliency and response type for both the identical, $F(1,31) = 6.405$, $p = .017$, $\eta_p^2 = .171$, and the similar condition, $F(1,31) = 11.561$, $p = .002$, $\eta_p^2 = .272$. However, the pattern of results again differed between conditions, as follows.

In the identical condition, the error was significantly larger when participants (incorrectly) responded similar, rather than identical, both for less, $t(31) = 2.950$, $p = .006$, and more salient items $t(31) = 6.286$, $p < .001$. This effect was particularly pronounced if the incorrect response was chosen for more salient items, with a significant difference between the two saliency levels, $t(31) = 2.520$, $p < .0171$. As these more salient items should be relatively easy to recognize as identical, the incorrect choice here suggests a decay of the memory trace, evident in a larger error. No significant difference between salience levels was observed for correct responses, $t(31) = 0.367$, $p < .716$.

In the similar condition errors were overall more comparable to each other. Somewhat counter-intuitively, and in contrast to the identical condition, errors were actually smaller if participants incorrectly responded 'identical', than if they correctly responded 'similar', $t(31) = 2.352$, $p = .025$, for less salient items. For more salient items, the reverse was true, with correct 'similar' responses associated with a smaller error than incorrect 'identical' responses, $t(31) = 2.470$, $p = .019$. Comparing errors for incorrect 'identical' responses to less and more salient items in the similar condition resulted in a significant difference, $t(31) = 2.628$, $p = .013$, with higher errors for more salient items. Errors for correct 'similar' responses in this condition were marginally different between more or less salient items, $t(31) = 1.741$, $p = .092$. Thus, while incorrect responses in the identical condition were associated with an increase in error with increasing saliency, in the similar condition, a decrease in error was observed for incorrect responses with increasing saliency.

In addition to the median-split analysis, the continuous responses in the location task also allowed to calculate the average correlations between saliency and location error across participants. I correlated the trial-wise saliency for each item with the location error for the same trial, separately for each condition by response type combination, and for each participant. The results of this analysis mirrored the data described above: Across participants mean correlations with saliency were not significant for correct 'identical' and correct 'similar' responses, $p > .261$. However, if participants incorrectly responded 'similar' in identical trials there was a marginally positive mean correlation with higher saliency predicting higher errors, $mean\ r = .1512$, $t(36) = 1.883$, $p = .068$. Similarly, if they incorrectly responded 'identical' in similar trials higher saliency again predicted higher errors, $mean\ r = .0871$, $t(37) = 2.733$, $p = .010$.

The results of the saliency analysis critically add to those described in the main text: With regards to the condition response, saliency effects were most pronounced in the similar condition, likely driven by interference due to low saliency. With regards to the precision in the location task, saliency also influenced responses in the identical condition: here incorrect responses to relatively easy to discriminate (high salience) items were associated with particularly low precision (high error). This finding is possibly more consistent with the idea that these memories might suffer from decay of the individual traces, evident in poor location memory, rather than interference between items.

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