On the limits of evidence accumulation of the preconscious percept

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Abstract

When a stimulus is repeated the memory representation for that stimulus is strengthened and performance in memory tests increases. To what extent this effect requires that each exposure elicits a fully-fledged conscious percept? In two Rapid Serial Visual Presentation (RSVP) experiments we explored whether the memory representations for words would accumulate evidence trough repeated exposure when none of those presentations induced a conscious percept. Participants were instructed to identify repeated items inserted in different RSVP streams and we isolated the first instance that an item was consciously perceived as repeating. The results showed that the probability of detecting a repetition for the first time was constant across repetitions. This effect signals a limit to the evidence accumulation process through repeated exposure. We discuss whether conscious perception modulates the decay of memory representations with below-threshold items resulting in extremely fleeting memory representations.

Keywords: Conscious perception, episodic memory, repetition effect, RSVP, evidence accumulation.

1. Introduction

It is uncontroversial to believe that memories for a stimulus are strengthened through repeated experience of that stimulus. Indeed, Endress and Potter (2014) have explicitly shown this to be the case, even for briefly fixated objects. However, a key question is the role of conscious perception in this process. In this respect, the scenario presented in Case 1 in figure 1 is not controversial; that is, if a stimulus is consciously perceived, some sort of “trace” (whether activation-based or synaptic) of that stimulus would typically form after the moment of awareness. Furthermore, such a trace could accumulate over repeated presentations, i.e. there would be *evidence accumulation*.

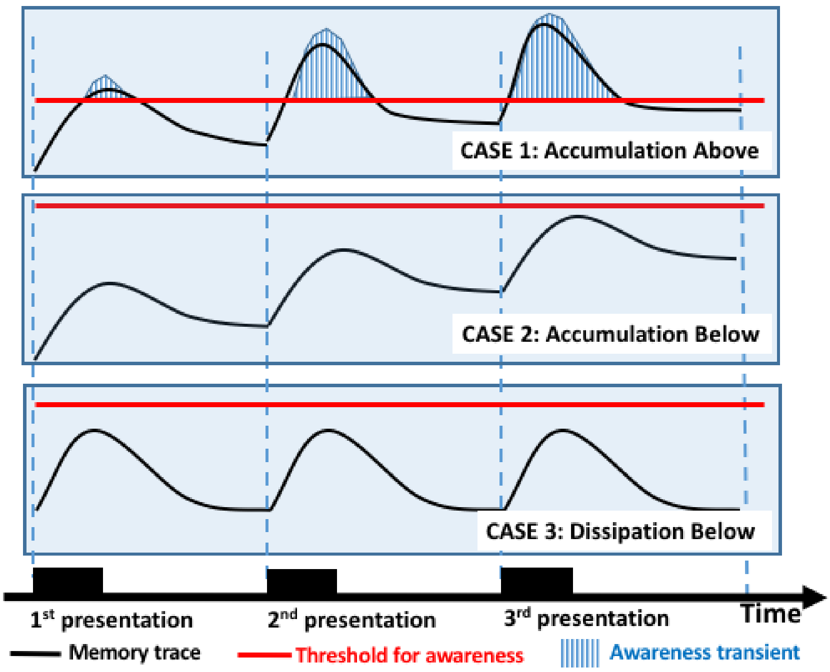

Figure 1: three theories of how the brain responds to repeated presentations. The stimulus sequence is shown in black as three presentations of the same stimulus. The awareness transient reflects the conscious experience of the presented stimulus. Three accumulation regimes are shown. CASE 1: evidence accumulates across presentations, each of which yields an, if only brief, conscious percept. CASE 2: evidence accumulates without conscious percepts. CASE 3: evidence dissipates between presentations, none of which generate a conscious percept.

What happens though, in the case of stimuli that do not reach awareness is less clear. That is, would it be possible for the trace of an item to strengthen, i.e. for evidence to accumulate, through repeated presentation if none of those presentations induced a conscious percept, such that conscious perception becomes more likely with further presentations, as in Case 2 of Figure 1? In contrast, it could be the case, as shown in Case 3, that stimuli that do not reach a threshold of awareness do not leave a trace that accumulates over multiple exposures.

This is the question we consider in this paper, viz, we seek to determine whether the brain behaves as Case 2 or Case 3 of figure 1. In other words, do representation traces for stimuli registered below the the awareness threshold, dissipate back to baseline so quickly that there is effectively no evidence accumulation for the preconscious percept? (How these different modes of evidence accumulation relate to relevant phenomena in the literature, such as subliminal priming, is considered in the Discussion section.)

To answer this question, one needs a means to present a lot of stimuli in such a way that many do not cross the awareness threshold. The natural way to do this is with Rapid Serial Visual Presentation (RSVP), for which it is known that only a small subset of the presented stimuli are reportable, or indeed recognisable (Bowman et al., 2013; Bowman, Filetti, Alsufyani, Janssen, & Su, 2014; Potter, 1976).

In fact, there are previous studies that have considered the progressive strengthening of memories with RSVP (Albrecht & Vorberg, 2010; Endress & Potter, 2014; Subramaniam, Biederman, & Madigan, 2000). For example, Endress and Potter (2014) reported that images (and words) presented more often across a number of Rapid Serial Visual Presentation (RSVP) streams were recognized more accurately in a final recognition test. Given that, as previously discussed, in RSVP studies, participants often show very poor recognition performance, Endress and Potter's findings are open to the interpretation that some items leave memory traces that gain strength through repetition, despite not being consciously perceived. That is, although we will ultimately argue against this position, Endress & Potter's findings open the possibility that Case 2 of figure 1 obtains and memories accumulate through repetition for the pre-conscious percept.

However, some studies have reported that most stimuli presented in RSVP do not display consolidation/evidence accumulation through repeated exposure. Subramanian, Biederman and Madigan (2000) presented participants with RSVP streams of drawings of objects. Participants were instructed to search for a target image. Crucially, some of the non-target pictures were presented 15 times on average before becoming a target. The results revealed an absence of a repetition effect; that is, participants were not better at detecting the targets that had previously been repeated relative to those presented once. In a similar vein, Bowman et al., (2014) presented participants RSVP streams of first names and they were instructed to search for a Fake Name (a name they were pretending was their name). In addition, in Experiment 3, they were instructed to search for frequently presented names; that is, they had to search for names simply on the basis that they were repeated. Importantly, these repeating names were presented as often as the Fakes (up to 50 times). The behavioral results (recall and recognition test at the end of the experiment) indicated that participants found it very hard to identify the repeated names; and consistent with this, in ERP findings, the Fake generated a clear P3 that was absent for the repeating name. As in Subramanian et al. (2000), participants were actively searching for an additional item (Target in Subramanian et al, Fake in Bowman et al), which arguably could hinder the encoding process of repeating items.

Taken together, the above described findings are far from offering a coherent picture. On the one hand, some studies raise the possibility that evidence accumulation is possible for non-retrievable (and thus not consciously perceived) stimuli presented in RSVP[1]. This would suggest that items naturally elicit (graded-strength) memory traces. On the other hand, other studies suggest that the capacity to form memory traces from the fleeting representations of items in RSVP is very limited. That is, despite the serial presentation of items in RSVP, unless an item is processed to the point that it reaches a state of awareness, evidence for it would not accumulate.

One can view the present study as shedding light on the nature of the discrepancies between the described findings. If the presentation of stimuli in RSVP results in memory representations of gradual strength, these representations may increase in strength with every repetition, facilitating retrieval. On the other hand, the encoding of items could follow a bottleneck behavior: a small number of stimuli would (enter consciousness and) be stored in stable WM representations, while the vast majority would not reach that stage. Importantly, the "missed" stimuli would not benefit from successive repetitions, since residual information would not survive the presentation of new items.

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[1] Our focus in this paper is specifically on access awareness (Baars, 2002; Block, 2007) which means that conscious perception can be associated with retrievability; that is, report is taken as an indicator of awareness.

In the previous studies that have considered the progressive strengthening of memories with RSVP (Subramanian, Biederman & Madigan, 2000; Endress & Potter, 2014), a repeating stimulus occurred incidentally in RSVP streams through the course of an experiment. Then a recognition test on the stimulus was inserted after a certain number of repetitions. This previous work, though, was not specifically focussed on *preconscious* evidence accumulation, which is our interest. That is, they did not probe memory in such a way that they could identify *the first time* a stimulus was seen as repeating, leaving the possibility that their recognition reports could have arisen after at least some previous presentations were consciously perceived, i.e. Case 1 in our figure 1. As a result, we have had to employ a somewhat different experimental paradigm to these previous studies. In particular, we could not rely on recognition memory tests at the end of each of a number of RSVP streams, since such a test could reveal the identity of a repeating (target) stimulus whether it had or had not been perceived in a stream to that point, thereby consciously priming its future perception. This would confound any test of an *intrinsic* below threshold build-up of evidence with repeated presentation.

We are interested in isolating the *first* instance at which a (non-primed) repeating item is consciously perceived as repeating. To obtain such a test, we have run an RSVP repetition experiment, where we instruct participants that a repeating item will be presented, but we do not identify it and participants are required to search for it simply on the basis that it repeats.

With this approach, we can test what turns out to be the key property for us, which is that (first) detection of repetition is invariant to the number of prior presentations, with the following procedure.

1) We determine the first instance at which an item is seen as repeating.

2) We assess whether the probability of this first instance is invariant to the number of prior repetitions; by determining the conditional probability of seeing a repetition, given that it has not been seen as a repetition before.

If this conditional probability, which we call the *first seen as rep. probability*, is indeed invariant across repetitions, there is no evidence accumulation before a repetition is first seen. This can be illustrated with reference to figure 1, where the accumulation inherent to Case 2 would ensure that the probability of first seeing (and then seeing as a repetition) would increase with each sub-threshold registration of a stimulus. This is because the distance to threshold would be reducing on each registration. In contrast, in Case 3, the probability of first seeing (and then seeing as a repetition) would not change with (below threshold) registration of a repeating stimulus. This interpretation of Cases 1 and 2 is confirmed in simulations in the appendix.

More specifically, we have designed two different tasks using RSVP of streams of words: (1) a Repetition task and (2) a Detection task. In the first of these, the repetition task, participants were instructed to search for a word that was repeated across trials/ streams. They were informed that they were going to see several streams of words and they must search for the repeated word. At the end of each trial/ stream, they had to answer the question “Which one was the repeated word?”. We varied the presentation time in two experiments (from an SOA of 17ms to 533ms). In this task, we tested to what extent participants can detect repeated items inserted in different RSVP trials. This enabled us to examine to what extent contents generated in RSVP can accumulate evidence through repetitions, with a key test being invariance to prior presentation of the first seen as rep. probability. To do this, we examined whether the number of presentations of a word increased the probability of first detecting the repeated word.

While, as we have discussed, the experimental paradigm we employ here is somewhat different to that used in (Subramanian, Biederman & Madigan, 2000; Endress & Potter, 2014), we believe our experiment and theirs are comparable. In particular, our experiment can be seen as a generous test of the evidence accumulation question, since we are *instructing participants to look for repetitions*. That is, if evidence does not accumulate preconsciously for repeating items, when participants are explicitly instructed to look for such items, it seems unlikely that is would incidentally, when participants are not instructed to look for them. Incidental build up is the approach in the Subramanian, et al and Endress & Potter experiments.

The results of the Repetition Task were compared with those of a Detection task, which effectively served as a baseline to compare against. In the Detection task, participants were instructed to search for pre-specified target words. This enabled us to explore to what extent participants can search for stimuli in RSVP on the basis of their perceptual properties. With the comparison of the two tasks, we aimed to illustrate the time-course of two fundamentally different types of search: one based on the perceptual features of task relevant items (Detection) and the other based purely on frequent occurrence (Repetition). Our findings will confirm that, consistent with previous work (Bowman et al, 2013; Potter, 1976;), the brain is exceptionally good at searching for pre-specified items, as per our detection task. In contrast, searching on the basis that an a priori unknown item occurs frequently, as per our repetition task, is much harder.

2. Method

2.1 Experiment 1

2.1.1 Participants

21 undergraduate students of the University of Birmingham took part in Experiment 1 in exchange for course credits. All were right handed, native English speakers and had normal or corrected-to-normal vision. The experiment conformed to British Psychological Society criteria for the ethical conduct of research and ethical procedures of the School of Psychology at the University of Birmingham.

2.1.2 Materials

36 English nouns were selected from the English Lexicon Project database (Balota et al., 2007) to serve as Targets. Additionally, 1800 English words were selected as Distractors from (Warriner, Kuperman, & Brysbaert, 2013). Two lists of Targets were created so that participants could perform the Detection and Repetition task on a different set of Targets. Both lists of Targets were controlled for word frequency, concreteness and emotional valence. All targets and distractor words had 6 letters and none of them were proper nouns. The same set of Distractors was used in both lists.

2.1.3 Procedure

RSVP streams were presented on a 24’’ LCD screen (refresh rate: 60Hz, resolution: 1600 x 1200) using custom PsychToolbox scripts running under Matlab 2016a. Stimuli were 16-point white (75% white) characters on a dark background (25% white). Participants were seated at 60cm from the screen.

The experiment was conducted individually in a quiet room. Each experimental session was divided into two tasks (Detection Task and Repetition Task). The order of tasks was counterbalanced (15 participants performed the Detection Task first and 16 participants performed the Repetition Task first). Each task consisted of 18 blocks (3 blocks per SOA condition: 33, 133, 233, 333, 433 and 533ms) presented in random order. The target was the same within a block and different across blocks.

Detection Task

Each block consisted of 10 trials. At the beginning of the block, participants saw the instruction "Search for the word:" in the upper part of the screen along with the target word presented at the centre of the screen for 2 seconds. Each trial started with the centred presentation of the fixation cross (+) for 500ms. Then a stream of 10 words was presented and a final item "######" at the end of the stream. The trial ended with the question "Have you seen the target word?". Participants responded to the question by pressing predetermined "yes" and "no" buttons. The target word was presented in 5 of the 10 trials of each block and the remaining 5 trials were target absent trials. The target word could be presented in any position of the stream except position 1st, 2nd, 9th and 10th. The duration of this session was approximately 25 minutes.

Repetition Task

Each of the 18 blocks of the Repetition Task consisted of 11 trials. The trials started with the instruction "Search for the repeated word". Then participants were presented with 11 trials with a similar structure as those of the Detection task. However, in this task, participants were instructed that one of the words presented during the first trial would be presented several times in the following trials. This first trial of the block was not followed by a question[2], while the remaining 10 trials were followed by the question "Have you seen the repeated word?". Participants typed the word that they considered was repeated or pressed "Enter" to continue with the next trial. As in the Detection task, the repeated item (RI) was presented in 5 of the 10 experimental trials, so that half of the experimental trials in a block did not contain the RI. Importantly, distractors did not repeat within a block. The administration of this task lasted approximately 28 minutes.

2.2 Experiment 2

[2] Note that in Bowman et al., (2014) participants were not instructed of the presence of the repeated name at a specific trial, making the task harder. This may explain why the repeating stimulus was detected less easily in Bowman et al., (2014).

The materials and procedure were the same as for Experiment 1. The only difference was that in this experiment a different set of SOAs was selected: 17, 50, 84, 117, 250 and 400ms.

2.2.1 Participants

24 undergraduate students from the University of Birmingham participated in Experiment 2 in exchange for course credits. None of these students had participated in Experiment 1. The same exclusion criteria were used in both experiments. The experiments performed conformed to British Psychological Society criteria for the ethical conduct of research and ethical procedures of the School of Psychology at the University of Birmingham.

3. Results

3.1 Repetition and Detection Task

Although the main piece of evidence we are seeking to identify is the estimation of the (accumulation) repetition effect in RSVP (which is described in the next section), the results described here –comparing the d' score of the Detection and Repetition task– give a global picture of the time-course of participants' performance in both task.

Experiment 1

We calculated participants' d' measures for both tasks. In the Detection task, the Hits, Misses, False Alarms and Correct Rejections were obtained from the "yes" and "no" responses. In the case of the Repetition Task, we considered as Hits all target-present trials where participants typed any word, even if it was not the Target. Similarly, we considered as False Alarms all trials where participants typed a word at the end of the trial but the repeated word was not presented. It is important to notice that the same criterion was used for the classification of responses as Hits or False Alarms[3]. Therefore, participants' d' measures above zero will correspond to their ability to distinguish trials where the repeated word was present from trials without the repeated word.

[3] The consequence of this is that any "incorrect-identity" repetition-seen response that could be made is truly an error response and is thus equally likely to arise in a target-present as a target-absent trial and is as likely to increase False Alarms as Hits. This will then just show up as a change in response-bias, but will not impact d-prime, which is how it should work in signal-detection theory. Figure E.1 in Appendix E shows performance in the repetition task using an alternative criterion: any string with a Levenshtein distance (the minimum number of single-character edits; insertions, deletions or substitutions) of 2 or less was accepted as a correct response.

A 2 (Task: Detection and Repetition) x 6 (SOA: 33, 133, 233, 333, 433, 533) within subjects ANOVA revealed that the d' values (see Figure 2 and Table 1) were significantly larger for the Detection Task (mean=2.87 and sd=1.52) than for the Repetition task (mean= 1.51 and sd=1.46), $F(1,20)=171.7$, $MSE = 115.78$, $p<0.001$. There was also a main effect of SOA, $F(5,100)=91.93$, $MSE = 32.85$, $p<0.001$. Unsurprisingly, d' values were larger for the long SOA conditions, see Table 1. The interaction was also significant $F(5,100)=7.75$, $MSE = 1.97$, $p<0.001$, showing the task effect was not constant across the SOA conditions. To analyse the interaction, we subtracted the d' values of both task and performed post-hoc comparisons across the SOA levels. Pairwise comparisons revealed that the task effect was larger at 133ms relative to 33, 333, 433, and 533ms (all ps<0.05, Holm corrected). Similarly, the task effect at 233ms was significantly larger than the task effect at 33ms ($p<0.05$, Holm corrected).

Experiment 2

A 2 (Task: Detection and Repetition) x 6 (SOA: 17, 50, 84, 117, 250, 400) within subjects ANOVA showed a main effect of Task, $F(1,23)=247.2$, $MSE=97.09$, $p<0.001$ (Detection task: mean= 2.40, sd=1.9; Repetition task: mean=1.24, sd=1.58). The main effect of SOA was also significant, $F(5, 115)= 164.4$, $MSE=61.56$, $p<0.001$. Finally, the interaction Task x SOA was significant $F(5, 115)= 15.17$, $MSE=4.92$, $p<0.001$ (see Figure 2 and Table 2).

Pairwise comparisons of the task effect (d' Detection task – d' Repetition task) across SOA conditions revealed that the task effect was significantly larger (all ps<0.05, Holm corrected) at 117ms relative to all other SOA conditions (17, 50, 250 and 400ms) except the 84ms condition ($p=0.67$, Holm corrected). In contrast, the task effect at 17ms was significantly smaller (all ps<0.05, Holm corrected) compared with any other SOA condition (50, 84, 117, 250 and 400ms).

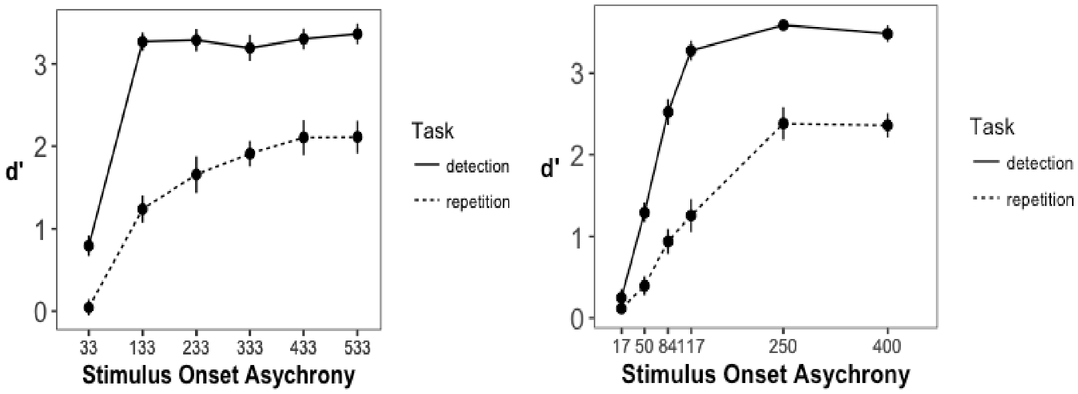

Figure 2. Results for experiments 1 (left) and 2 (right). The graph shows the d' scores for the Detection and Repetition tasks across the SOA conditions. Error bars indicate standard errors of the mean.

Table 1. Mean d' values and (standard deviations). Experiment 1

TASK	SOA					
	33	133	233	333	433	533
DETECTION	0.79 (0.57)	3.27 (0.51)	3.28 (0.62)	3.19 (0.60)	3.30 (0.58)	3.36 (0.56)
REPETITION	0.04 (0.44)	1.24 (0.76)	1.65 (1.02)	1.91 (0.71)	2.11 (0.97)	2.11 (0.91)

Table 2. Mean d' values and (standard deviations). Experiment 2

TASK	SOA					
	17	50	84	117	250	400
DETECTION	0.25 (0.51)	1.29 (0.59)	2.52 (0.77)	3.27 (0.60)	3.59 (0.31)	3.48 (0.5)
REPETITION	0.12 (0.30)	0.39 (0.57)	0.94 (0.75)	1.25 (1)	2.38 (0.98)	2.36 (0.74)

The effect of repetition in RSVP

In this section, we assess the repetition effect on the probability of identifying a repeated item (RI) for the first time in the Repetition task. Specifically, we tested whether the probability of identifying the RI increased as a function of how many times the RI had been presented. In the Repetition Task, participants were presented the RI five times (1st, 2nd, 3rd, 4th and 5th repetition) per block. This allowed us to calculate the probability of identifying the target at each repetition for the first time. Note that, contrary to the procedure adopted by the analysis described above (where any string of letters typed by participants was included in the calculation of Hits and False Alarms) for the present analysis, we only considered responses as correct if the RI was typed. To do that, the number of words correctly identified for the first time at repetition j (1 to 5) was divided by the number of blocks where the RI was missed at every repetition before j. That is, at repetition 1, the number of RIs identified (as repeating) at that repetition was divided by the total number of blocks (3) at each SOA condition. For repetition 2, the number of RIs identified (as repeating) for the first time at repetition 2 was divided by the total number of blocks where the RI was missed at repetition 1, and so on. See Appendix 1 for a formal definition of this measure.

To calculate this probability at every repetition it is essential that participants missed some repetitions, since the first-seen measure depends on the number of repetitions where the target was not detected. From the results of the repetition task (see Figure 2, it is evident that participants were very good at detecting repetitions at long SOAs (>200ms). They had identified correctly on average more than 50% of the words by the third repetition. Consequently, we considered that the data available at these long SOA conditions did not give enough power to provide a good estimation of the effect of repetition. The opposite pattern was found at the shortest SOAs (33ms, Experiment 1; 17ms, Experiment 2) where participants were effectively at floor. Therefore, the data submitted to statistical analysis were those corresponding to the SOA conditions: 133ms in Exp. 1, and 50, 84 and 117 in Exp.2). For completeness of reporting, Appendix C, Tables 5 and 6 summarise the full set of results.

Experiment 1

The data (see Table 3) were analysed using a probit mixed-effect model, with the lme4 package in R (Bates, Mächler, Bolker, & Walker, 2015). Repetition (1^{st} to 5^{th}) was included as a fixed factor. The random structure of the model only included the intercept of the Participant factor. More complex models (including those with slopes in the random factor) did not reach convergence. A Chi-square test from the probit linear mixed model results showed a non-significant effect of repetition ($p > 0.9$).

The non-significant effect of the repetition indicates that we cannot reject the Null Hypothesis that there is no effect of Repetition. To assess the extent in which our data are more consistent with the Null Hypothesis, we calculated the Bayes Factor from the Bayesian Information Criterion (BIC; Raftery, 1995) of two models following the approximation suggested by Wagenmakers (2007)[4]: the full model (Repetition + random intercept per participant) and the restricted model (Intercept + random intercept per participant). The Repetition factor was included as a linear regressor (1 to 5) to model the "build-up" mechanism proposed by Endress and Potter (2014). The BF_{01} (null/alternative) was 6.90. Following the classification scheme of Raftery (1995) we concluded that this is positive evidence (BF 3-20) for the Null Hypothesis of no Repetition effect.

Experiment 2

We analyzed the data from Experiment 2 using the same methodology as in Experiment1. The data of the probability of first identification as a repetition (see Figure 3 and Table 4) were analyzed with a probit linear mixed model with SOA (50, 84, 117) and Repetition (1^{st} to 5^{th}) as fixed factors. The random structure of the model included the intercept per participant. The Chi-square test from the model revealed a significant effect of SOA, $\chi2(3) = 7.46$, $p = 0.024$, and no significant effect of Repetition nor the interaction SOA x Repetition (both $ps>0.8$).

The Bayes Factor between the BIC of the full model (SOA, Repetition and SOA x Repetition) and the restricted model (SOA) showed that the restricted model was favored by a factor of 9.077142e+13. Finally, the BF for each SOA condition between the full model (Repetition + random intercept of the participants) and the Null (intercept only + random intercept of the participants) revealed the following results: BF_{01} SOA 50ms = 8.09, BF_{01} SOA 84ms = 10.18, BF_{01} SOA 117ms = 9.99. As from experiment 1, the Bayes Factor analysis indicates that the results from experiment 2 favored the Null Hypothesis of an absence of a Repetition effect.

[4] exp((BIC_1 - BIC_0)/2)

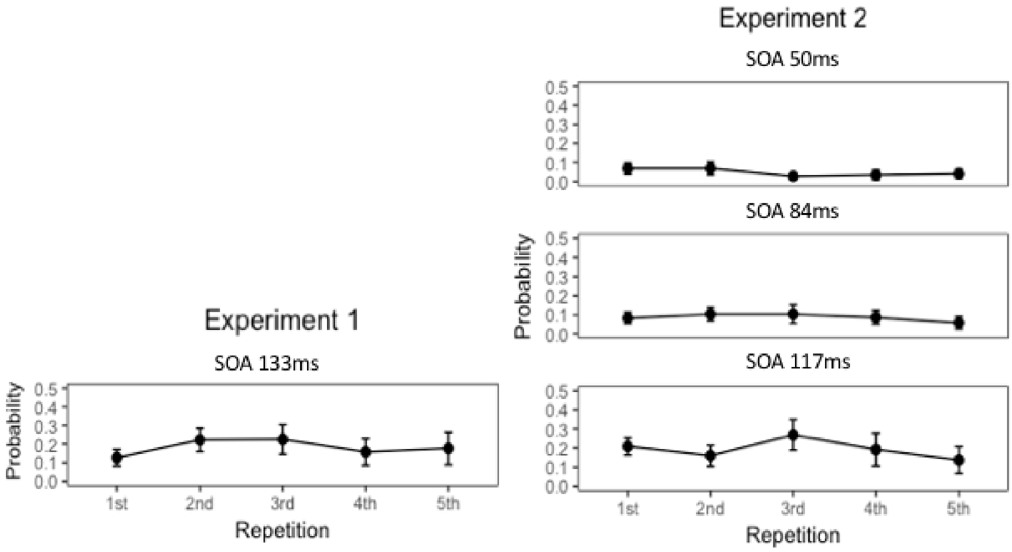

Figure 3. Results for experiments 1 (left) and 2 (right). The graph shows the probability of first detecting the target (as repeating) after every repetition. Error bars indicate standard errors of the mean.

Table 3. Mean probability of first detection as a rep. and (standard deviations). Experiment 1

	Repetition				
SOA	1	2	3	4	5
133	0.13(0.2)	0.22(0.29)	0.23(0.35)	0.16(0.3)	0.18(0.36)

Table 4. Mean probability of first detection as a rep. and (standard deviations). Experiment 2

	Repetition				
SOA	1	2	3	4	5
50	0.07(0.14)	0.07(0.17)	0.03(0.1)	0.03(0.12)	0.04(0.11)
84	0.08(0.15)	0.1(0.17)	0.1(0.24)	0.09(0.18)	0.06(0.16)
117	0.21(0.22)	0.16(0.27)	0.27(0.38)	0.19(0.38)	0.14(0.29)

4. Discussion

In two studies, participants were presented streams of words at different presentation rates, while performing a detection or a repetition task. The repetition task required participants to search for repeated words across several streams (different trials). The detection task instructed participants to search for pre-specified target words within each trial. Participants were able to complete both tasks, with performance being considerably better in the easier detection task.. More importantly, in the repetition task the probability of detecting a repetition for the first time did not increase with the number of repetitions. This suggests that the performance in the repetition task was not aided by evidence accumulation across repeated instances of the same word. This result has implications for our understanding of how fleeting representations are processed and remembered. At SOAs in the range of 84-133 ms, participants exhibit excellent performance on the detection task, with d' scores well above 2.0. Thus, it must be the case that most of the words are individually being processed to some degree, and yet at these same rates, repetition detection does not benefit from evidence accumulation.

In previous studies, the absence of accumulation effects had been obtained in conditions where performance in memory tasks was extremely poor. Subramanian et al., (2000) showed that non-targets repeated up to 15 times were not detected better once they became targets in a detection task. Importantly, they reported that, in similar conditions, recognition for non-targets in a forced-choice task was at chance. In Bowman et al., (2014), participants found it very hard to detect repeated names —presented up to 50 times— even when they were instructed to search for them. These findings pointed to a failure of memory encoding for items in RSVP. It seems that items neither accumulated evidence nor were easily retrieved, since there was little evidence for memory representations that could carry out those functions. The present results agree with those of (Bowman et al., 2014) and Subramanian et al., (2000) in that no repetition accumulation effect was observed. However, contrary to these studies, participants' performance in the repetition task was not at chance. That is, even though participants' capacity to notice repetitions was somewhat spared, the repetition accumulation effect was absent.

In contrast with the present results, in other studies, repetition demonstrably improved recognition performance, even in RSVP experiments. For example, Endress and Potter (2014) found that items presented more often in RSVP trials were recognized more accurately. They suggested that the repeated instances of items in RSVP build-up and result in stable long term memory representation. Our results could be signalling one fundamental limit of this mechanism. While it might be true that repetition facilitates retrieval, it could be that the retrievability (\ conscious perception) of items is a necessary condition for any repetition accumulation effect, as per case 1 of figure 1. Alternatively, it would have been possible that memory representations could accumulate evidence through repeated exposure prior to being strong enough to be consciously perceived and explicitly retrieved, i.e. case 2 of figure 1. Our findings contradict this notion, at least in experimental paradigms such as RSVP. Our results showed no repetition accumulation effect prior to the explicit recognition of words (as repeating) for the first time, i.e. case 3 of figure 1. This opens the possibility that in RSVP, the evidence accumulation process is restricted to those items that have been consciously perceived and thus encoded in strong memory representations, at least sufficiently strong to support explicit recognition. In fact, the findings in Endress and Potter (2014) are consistent with this possibility. Since the benefit of repetitions was only apparent in a final recognition test (by comparing accuracy for items presented less and more often), it could be that only those items consciously detected were those that improved with repetitions after that point.

Alternatively, the absence of a repetition effect could be attributed to memory capacity limits. Some stimuli would not be encoded in memory since memory limits are reached –given that streams consisted of 10 words (above short-term memory span). However, the d´ results of the Repetition Task contradict this interpretation. As can be observed in Figure 2, performance steadily improves up to asymptotic levels at slow presentation rates (SOA >200ms). If performance in the Repetition Task were to be explained only by memory capacity limits, no effect of presentation rate would be expected. Instead, SOA strongly modulated the results, suggesting that the presentation conditions (duration on screen and masking by subsequent items) played a crucial role. Taken together, the results of the Repetition Task seem to indicate that, in respect to memory encoding, items in RSVP could result in two qualitatively different types of representations. Some items could be encoded in sufficiently strong memory representations that successful explicit memory recognition is possible. On the other hand, most items may only elicit extremely fleeting “percepts” that would not survive the presentation of new items.

The present results do not contradict the notion that the presentation of items in RSVP can facilitate/prime the processing of subsequent stimuli, which can be considered an alternative form of evidence accumulation. Priming effects are very unlikely to be observed in a paradigm such as the Repetition Task. The distance between RIs –both in terms of number of intervening stimuli and duration– is relatively long and priming effects tend to be inversely related to the gap between items of interest (Ferrand, 1996). Alternatively, priming might have an effect in a recognition task (and the Repetition Task can be conceived as a continuous recognition task) by increasing the familiarity of repeated items. However, it is unlikely that our Repetition Task could be performed on the basis of familiarity decisions given that the format of the task, where an explicit report of the identity of the RI is required, makes the task similar to paradigms (such as recall), which rely on recollection processes – and not familiarity.

Are unidentified instances of RIs below threshold? The definitive answer to this question might ultimately require a resolution of the ongoing debate about the existence of phenomenological consciousness (Block, 2007; Cohen & Dennett, 2011). Indeed, we cannot rule out the possibility of phenomenological awareness of items presented in RSVP, i.e. that they are perceived, but forgotten before the end of the stream, see Figure 4. However, the most commonly accepted view in the RSVP literature is that the report of items at the end of the stream is taken as the behavioural correlate of conscious perception (for example: failure to report items in the attentional blink window) (Bergström & Eriksson, 2014). In the present experiment, the missed repetitions of RIs could similarly be interpreted as instances of below threshold stimuli.

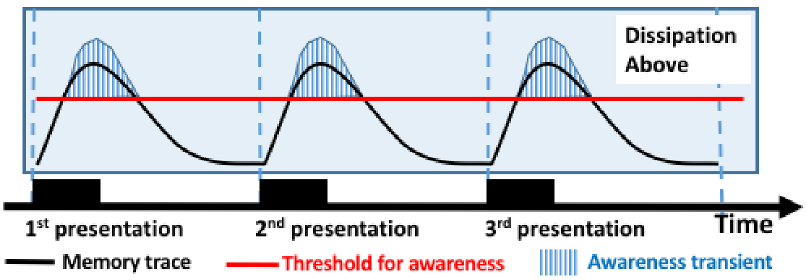

Figure 4. Further possibility for how the brain responds to repeated presentations. The stimulus sequence is shown in black as three presentations of the same stimulus. The awareness

transient reflects the conscious experience of the presented stimulus. Evidence dissipates between presentations, all of which generate a conscious percept.

This said, even if one accepts the contribution of phenomenological awareness to perception in RSVP, i.e. that items in this presentation format could be consciously perceived, but then rapidly forgotten, our line of reasoning is not in fact contradicted. That is, we have demonstrated a failure of evidence accumulation of repeated presentations, and if some of these “prior” presentations elicited above threshold experiences that were then forgotten, that would just represent evidence for the even stronger claim, that it is also possible that evidence does not accumulate for items that are consciously perceived. Importantly, though, it would seem highly unlikely that every prior presentation of the RI is consciously perceived and then forgotten. Our key findings are based upon streams with SOAs between 50 and 133ms; it seems inconceivable that every item in a 10 item stream at such SOAs would be consciously perceived. Accordingly, even if some RIs are consciously perceived and then forgotten, there remain some that would not, whose existence is sufficient to carry our claim.

The absence of apparent evidence accumulation (for stimuli in RSVP) could be the consequence of encoding processing limits of a similar nature to those responsible for other empirical findings such as the Attentional Blink (Raymond, Shapiro, & Arnell, 1992) and Repetition Blindness (Kanwisher, 1991). 2-stage theories of temporal attention (Bowman & Wyble, 2007; Chun & Potter, 1995) propose a first stage of large capacity where the attributes of items are extracted and a second stage where items are consolidated in WM. The memory encoding of items in our experiments seems to follow a 2-stage behaviour, where only a few items would break through to a second stage of consolidation into a durable representation (Wyble, Bowman, & Nieuwenstein, 2009). Indeed, the encoding of stimuli may depend on (what could be considered) random factors associated with presentation and processing (e.g. how effective the masking induced by the following item). This 2-stage interpretation gains further support if we compare the results of our repetition task with those of the detection task. Participants are much better at detecting pre-specified task-relevant items at any SOA condition than searching for repetitions. As can be observed in figure 2, at presentation rates close to 10/s, participants are almost at ceiling at discriminating target-present from target-absent streams. This is consistent with (Potter, 1976), and what was called (Sub)liminal Salience Search in (Bowman et al., 2013). It also fits with the idea of featural and semantic information being extracted in a first large-capacity stage; and a natural prediction then is that most items could be detected on the basis of their task relevant properties, which is in agreement with the results of the Detection Task.

The findings also fit with a stronger claim, viz, that a key aspect of conscious perception is supporting *episodic* encoding of items, a position that Kanwisher has also argued for (Kanwisher, 2001). One interpretation of the repetition task is that it is episodic in nature: to know that a previous instance has occurred, an individuated representation of that earlier occurrence needs to be represented in memory. This is exactly the role of tokens in the Simultaneous Type/ Serial Token model (Bowman & Wyble, 2007): when bound, they indicate the occurrence of a type. This system detects a repetition when the same type is bound to two tokens. Thus, tokens provide durable representations of event occurrences. If the preconscious percept does not induce a durable representation, it certainly cannot provide a tokenized (episodic) representation. This leaves the possibility that our subconscious is, strictly speaking, *episodically blind* and even potentially that the very process of perceiving involves episodically tagging experiences. This is what we call the Tokenized Percept Hypothesis, from which we will seek in future experiments to find further evidence.

In summary, we have shown an effect of explicit recognition of items in the absence of any benefit obtained from successive repetition. These results suggest that the process of episodic encoding in RSVP follows a bottleneck behaviour, where most items fail to be durably consolidated in memory or even to leave any memory trace that is able to support evidence accumulation. Combined with the results of the detection task, the findings suggest that in fast RSVP streams, items can be discriminated easily on the basis of their perceptual attributes in conditions where only a small subset of them can be durably encoded. Taken together, these results agree with 2-stage theories of temporal attention, where a first stage of large capacity consists of the activation of the perceptual properties of items (enabling, for example, effective detection performance) and a second stage encodes a subset of items into durable WM. Insofar as it is assumed that conscious percepts are those that can be reported/retrieved, these results suggest that conscious perception is required for an additional function: the accumulation of evidence through repetition.

Appendices

Appendix A

Mathematical characterisation

Assume a sequence of N trials in which an item repeats, index these trials with the natural numbers $[1{:}N] \subseteq \mathbb{N}$. Define the predicate $See\_Repeating(j)$ to hold if and only if the repeating item is seen as repeating on the jth trial. Then, we define *first seen as rep. probability* as follows. Eq. (A.1):

$$p_i = p(\ See\_Repeating(i)\ \mid\ \forall j \in \mathbb{N}\ (1 \leq j < i)\ \cdot\ \neg\ See\_Repeating(j)\ )$$

That is, p_i is the conditional probability that the repeating item is seen as repeating on trial i, given that on all previous trials it has *not* been seen as repeating.

The key property we are interested in is *invariance to number of repetitions*, which holds if and only if, $\forall i, j \in \mathbb{N}\ (1 \leq i, j \leq N)\ \cdot\ p_i = p_j$.

Appendix B

Model

We have also implemented a very simple probabilistic model of the two evidence accumulation cases to confirm our intuition re. the invariance of conditional probabilities. Our objective was not to provide a full mechanistic investigation of evidence accumulation in an RSVP context, but rather to simply confirm our intuition that the invariance to number of repetitions property that is central to our argument does follow from a "simple as possible" interpretation of a lack of evidence accumulation compared to accumulation.

As we did for the mathematical definitions, assume a sequence of N trials in which an item repeats, index these trials with the natural numbers $[1{:}N] \subseteq \mathbb{N}$. Our models are defined in terms of the updating of two predicates across these trials:

1) $See(i)$ is $true$ if and only if the repeating item is seen on trial i.
2) $See\_Repeating(i)$ is $true$ if and only if the repeating item is seen *as repeating* on trial i.

Note that the target can be seen, without being seen as repeating, which requires it to have been seen multiple times. As a result, we distinguish between *See*ing and *See*ing as *Repeating*.

The *basic model* is defined by the following rules, where we sample ones and zeros according to Bernoulli distributions, i.e. from $Bern(q)$, where q is the probability of getting a one. Eq. (B.1):

$$See(1) = X{\sim}Bern(p_i)$$

$$See\_Repeating(1) = 0$$

$$\forall i \in \mathbb{N}\ (1 < i \leq N) \cdot$$

$$See(i) = \begin{cases} X{\sim}Bern(p_i) & , if\ \forall j\ (1 \leq j < i)\ \cdot\ \neg See(j) \\ 1 & , \quad otherwise \end{cases}$$

$$See\_Repeating(i) = \begin{cases} 1 & , if\ See(i-1)\ \vee See\_Repeating(i-1) \\ 0 & , \quad otherwise \end{cases}$$

This basic model can be specialised into the two versions we are interested in by specifying how p_i is calculated.

No Evidence Accumulation is obtained by setting p_i to a constant, say p $(0 \leq p \leq 1)$.

Evidence Accumulation is obtained by setting p_i to a monotonically increasing function of i, which does not go out of bounds. The easiest way to do this is to assume simple linear evidence accumulation, where we first define b and C such that, $0 < b < 1$, $0 \leq C < 1$ and $(b.N) + C \leq 1$, in order that accumulation stays within bounds. Then we define the following. Eq. (B.2):

$$p_i = (b.i) + C$$

Note, b is assumed to be sufficiently above zero to exclude seemingly no evidence accumulation patterns being generated.

Other more complex monotonically increasing functions could be used.

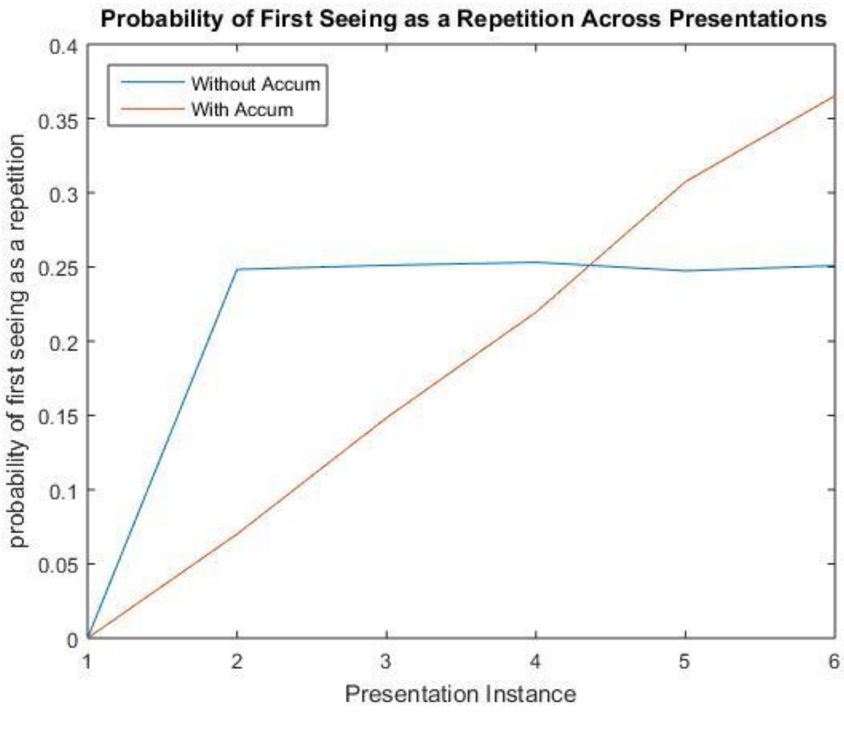

Figure B.1: Results of simulations: the fixed probability for the Without Evidence Accumulation case, p in the model description above, was set to 0.25, while $b = 0.075$ and

$C = 0.075$ in the With Evidence Accumulation case. The first-seeing as a rep. probability is shown on the y-axis. The With Accum case clearly shows an increasing first-seeing as a rep. probability across repetitions, while the Without Accum case shows no increase in the first-seeing as a rep. probability from the second presentation onwards. Note, a repetition cannot be seen at first presentation, i.e. position one.

Modelling Results

Simulation results are presented in figure 4. The average across 8000 simulated blocks for each of Without and With Evidence Accumulation are presented. Each block reflects six presentations of the repeating item. For each repetition instance, we calculate the first-seeing as a rep. probability, across all the blocks. The fixed probability for the Without Evidence Accumulation case, p in the model description above, was set to 0.25 in the simulations, while $b = 0.075$ and $C = 0.075$ in the With Evidence Accumulation case.

Appendix C

Table C.1 Mean probability of first identification as a rep. and (standard deviations). Experiment 1

	Repetition				
SOA	1	2	3	4	5
33	0.02 (0.07)	0 (0)	0 (0)	0 0)	0 (0)
133	0.13 (0.2)	0.22 (0.29)	0.23 (0.35)	0.16 (0.3)	0.18 (0.36)
233	0.29 (0.22)	0.4 (0.34)	0.42 (0.47)	0.42(0.48)	0.19 (0.38)
333	0.33 (0.28)	0.44 (0.39)	0.55 (0.46)	0.67 (0.44)	0.25 (0.50)
433	0.44 (0.33)	0.46 (0.44)	0.27 (0.39)	0.36 (0.46)	0.25 (0.47)
533	0.44 (0.29)	0.69 (0.39)	0.44 (0.47)	0.33 (0.53)	0.12 (0.25)

Table C.2 Mean probability of first identification as a rep. and (standard deviations). Experiment 2

	Repetition				
SOA	1	2	3	4	5
17	0.01 (0.07)	0 (0)	0 (0)	0 (0)	0.01 (0.07)
50	0.07 (0.14)	0.07 (0.17)	0.03 (0.1)	0.03 (0.12)	0.04 (0.11)
84	0.08 (0.15)	0.1 (0.17)	0.1 (0.24)	0.09 (0.18)	0.06 (0.16)
117	0.21 (0.22)	0.16 (0.27)	0.27 (0.38)	0.19 (0.38)	0.14 (0.29)
250	0.58 (0.30)	0.35(0.40)	0.43 (0.47)	0.30 (0.49)	0.43 (0.54)
400	0.57 (0.25)	0.60 (0.47)	0.35 (0.48)	0.57 (0.54)	0.33 (0.59)

Contrary to the case of short SOAs, performance at long SOAs (>200ms) increased between the first and second repetition (this pattern is observed in 5 out of 6 long SOA conditions). However, in this analysis, high performance at any repetition entails a loss of power. The underlined probabilities in the table are those where the available data was less than 40% of the data available at the first repetition. When so little data is available, the conditional probability can be considered unreliable. That is, at long SOAs, by the third repetition most participants had identified all the RIs. This emphasizes the fact that when the presentation is clearly above threshold the task is trivially easy. In contrast, at short SOAs participants found it very difficult to identify the RIs, which reinforces the view that it is very difficult to search for items on the basis of episodic information (repetitions) when items are presented at or below threshold.

Appendix D

Experimental stimuli (targets) used in Experiments 1 and 2.

Words	**WF**	**AoA**	**Concreteness**	***Familiarity***
List1				
rubber	15	289	596	547
cherry	6	317	611	514
butter	27	206	618	615
muscle	42	397	573	540
cellar	26	361	572	467
cotton	38	306	608	521
avenue	46	372	539	529
fiddle	2	367	582	465
lawyer	43	481	569	520
stable	30	292	562	519
palace	38	294	579	462
timber	19	403	578	440
school	492	228	573	582
racket	5	386	562	486
kettle	3	274	602	551
rabbit	11	206	635	523
kennel	3	322	611	449
hammer	9	278	605	515
Mean	47.5	321.06	587.5	513.61
List1				
pigeon	3	325	609	499
square	143	250	516	576
pocket	46	228	578	590
cavern	1	433	534	400
copper	13	428	547	491
bridge	98	289	623	561
thread	15	267	607	522
orange	23	203	601	567
rattle	5	261	549	448
driver	49	283	553	593
mother	216	144	579	632
banker	5	392	547	524
beggar	2	364	533	435
barrel	24	319	590	487
weapon	42	375	560	517
button	10	192	613	573
singer	10	314	553	548
branch	33	303	583	529
Mean	41	298.33	570.83	527.33

WF = Word frequency; AoA = Age of Acquisition.

Appendix E

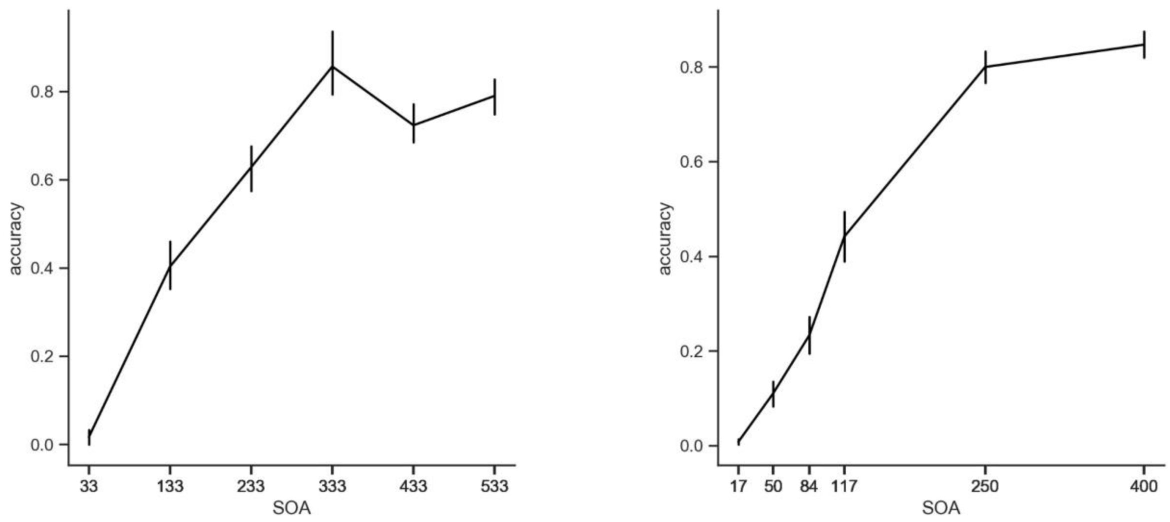

Figure E.1. Accuracy (correct identification of the repeated items) for Experiment 1 (left) and Experiment 2 (right).

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References:

Albrecht, T., & Vorberg, D. (2010). Long-lasting effects of briefly flashed words and pseudowords in ultrarapid serial visual presentation. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *36*(5), 1339–1345. doi:10.1037/a0019999

Baars, B. J. (2002). The conscious access hypothesis: origins and recent evidence. *Trends in Cognitive Sciences*, *6*(1), 47–52. doi:10.1016/S1364-6613(00)01819-2

Balota, D. A., Yap, M. J., Cortese, M. J., Hutchison, K. A., Kessler, B., Loftis, B., … Treiman, R. (2007). The english lexicon project. *Behavior Research Methods*, *39*(3), 445–459. doi:10.3758/BF03193014

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*(1), 1–48. doi:10.18637/jss.v067.i01

Bergström, F., & Eriksson, J. (2014). Maintenance of non-consciously presented information engages the prefrontal cortex. *Frontiers in Human Neuroscience*, *8*, 938. doi:10.3389/fnhum.2014.00938

Block, N. (2007). Consciousness, accessibility, and the mesh between psychology and neuroscience. *Behavioral and Brain Sciences*, *30*(5–6), 481–99; discussion 499. doi:10.1017/S0140525X07002786

Bowman, H., Filetti, M., Alsufyani, A., Janssen, D., & Su, L. (2014). Countering countermeasures: detecting identity lies by detecting conscious breakthrough. *Plos One*, *9*(3), e90595. doi:10.1371/journal.pone.0090595

Bowman, H., Filetti, M., Janssen, D., Su, L., Alsufyani, A., & Wyble, B. (2013). Subliminal salience search illustrated: EEG identity and deception detection on the fringe of awareness. *Plos One*, *8*(1), e54258. doi:10.1371/journal.pone.0054258

Bowman, H., & Wyble, B. (2007). The simultaneous type, serial token model of temporal attention and working memory. *Psychological Review*, *114*(1), 38–70. doi:10.1037/0033-295X.114.1.38

Chun, M. M., & Potter, M. C. (1995). A two-stage model for multiple target detection in rapid serial visual presentation. *Journal of Experimental Psychology. Human Perception and Performance*, *21*(1), 109–127.

Cohen, M. A., & Dennett, D. C. (2011). Consciousness cannot be separated from function. *Trends in Cognitive Sciences*, *15*(8), 358–364. doi:10.1016/j.tics.2011.06.008

Endress, A. D., & Potter, M. C. (2014). Something from (almost) nothing: buildup of object memory from forgettable single fixations. *Attention, Perception & Psychophysics*, *76*(8), 2413–2423. doi:10.3758/s13414-014-0706-3

Ferrand, L. (1996). The masked repetition priming effect dissipates when increasing the inter-stimulus interval: Evidence from word naming. *Acta Psychologica*, *91*(1), 15–25. doi:10.1016/0001-6918(95)00010-0

Kanwisher, N. (1991). Repetition blindness and illusory conjunctions: errors in binding visual types with visual tokens. *Journal of Experimental Psychology. Human Perception and Performance*, *17*(2), 404–421.

Kanwisher, N. (2001). Neural events and perceptual awareness. *Cognition*, *79*(1–2), 89–113.

Potter, M. C. (1976). Short-term conceptual memory for pictures. *Journal of Experimental Psychology. Human Learning and Memory*, *2*(5), 509–522.

Raymond, J. E., Shapiro, K. L., & Arnell, K. M. (1992). Temporary suppression of visual processing in an RSVP task: an attentional blink? . *Journal of Experimental Psychology. Human Perception and Performance*, *18*(3), 849–860. doi:10.1037/0096-1523.18.3.849

Reder, L. M., Nhouyvanisvong, A., Schunn, C. D., Ayers, M. S., Angstadt, P., & Hiraki, K. (2000). A mechanistic account of the mirror effect for word frequency: a computational model of remember-know judgments in a continuous recognition paradigm. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *26*(2), 294–320. doi:10.1037/0278-7393.26.2.294

Subramaniam, S., Biederman, I., & Madigan, S. (2000). Accurate identification but no priming and chance recognition memory for pictures in RSVP sequences. *Visual Cognition*, *7*(4), 511–535. doi:10.1080/135062800394630

Wagenmakers, E.-J. (2007). A practical solution to the pervasive problems ofp values. *Psychonomic Bulletin & Review*, *14*(5), 779–804. doi:10.3758/BF03194105

Warriner, A. B., Kuperman, V., & Brysbaert, M. (2013). Norms of valence, arousal, and dominance for 13,915 English lemmas. *Behavior Research Methods*, *45*(4), 1191–1207. doi:10.3758/s13428-012-0314-x

Wyble, B., Bowman, H., & Nieuwenstein, M. (2009). The attentional blink provides episodic distinctiveness: sparing at a cost. *Journal of Experimental Psychology. Human Perception and Performance*, *35*(3), 787–807. doi:10.1037/a0013902

Wyble, B., Wade, G., & Hess, M. (2018, January 31). Stream. Retrieved from osf.io/tdvxm