

Structural disorder facilitates future memory decisions

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Abstract

It is well known that perception and cognition are systematically biased towards the recent past. That is, a decision about the current state of a perceptual feature (e.g., orientation) can be predicted based on a recent state of the same feature. Such serial dependencies have been demonstrated across perception, memory, and cognition, and have been jointly attributed to an adaptive mechanism meant to promote stability in a constantly changing environment. Here, we argue that this adaptive mechanism prioritizes past information on the most basic structural level, such that the strength of the attractive bias is modulated by the amount of structural coherence in stimuli. We presented visual patterns of varied structural disorder (randomness) prior to a recognition memory decision that required discriminating between trained and novel visual patterns. Both highly generic geometrical shapes and completely random patterns failed to elicit an effect on decisional response times. By contrast, we found recognition memory decisions to be significantly faster in trials where the irrelevant probe pattern was “optimally” random. This result suggests that decision-making is influenced by the past’s informational worth. More importantly, it suggests an optimal amount of uncertainty to facilitate future decisions.

Word count: 193

1. Introduction

Serial dependence (Fischer & Whitney, 2014; Liberman et al., 2014; Kiyonaga et al., 2017) is the adaptive tendency of the cognitive and perceptual systems to integrate past information into current percepts so as to inform current decisions. It has been shown to occur in the perception of static visual features (Fischer & Whitney, 2014; Liberman et al., 2014; Manassi et al., 2023; Cicchini et al., 2024; Pascucci et al., 2023), perception of motion (You et al., 2023; Bae & Luck, 2020; Suarez-Pinilla et al., 2018), memory decisions (Malmberg & Annis, 2012; Fornaciai & Park, 2020), perceptual decision-making (Annis & Malmberg, 2013; Fornaciai & Park, 2018; Collins, 2022), and metacognition (Rahnev et al., 2015; Mei et al., 2023; Kantner et al., 2019; Aguilar-Lleyda et al., 2021). Importantly, serial dependence in decisions has been shown to transfer across interleaving cognitive tasks (Kantner et al., 2019), suggesting it is a stable phenomenon not tied to the current context. Therefore, serial dependence can be grasped as a symptom of the continuous nature of cognition – what has been termed a “continuity field” (Fischer & Whitney, 2014; Manassi & Whitney, 2024).

Continuity fields seem to serve two distinct but fundamental adaptive purposes. First, they allow us to perceive the world in a smoother and less disruptive manner (Manassi et al., 2017; Manassi & Whitney, 2022; Manassi & Whitney, 2024) by integrating information over time and canceling out perceptual noise, thereby promoting less noisy percepts. Second, by integrating prior information into the current percept, continuity fields allow us to improve our knowledge about the current state of the world, thereby eliciting effects that go beyond reproduction bias (Cicchini et al., 2018; Moscoso et al., 2023). Here we argue that this second property of continuity fields does not occur universally. Rather, whether or not past information influences current decisions would depend on the informational worth of the past stimulus,

decision, or environment. Specifically, increasing the amount of randomness by introducing structural disorder in a stimulus would decrease the informational gain associated with it, thereby decreasing the degree to which it impacts future perception. Importantly, we suggest that this effect would be robust irrespective of attentional modulation effects.

In the experiment described below, observers had to perform a recognition memory task involving simple visual patterns where the amount of structural disorder in each pattern was systematically varied. Prior to each memory decision, an irrelevant probe pattern was briefly presented and did not require a decision. We found an “optimal” amount of disorder in an irrelevant probe pattern to decrease the response time needed to arrive at a decision about the target stimulus. On the other hand, responses in trials involving generic geometrical shapes and fully random patterns as probes did not differ from responses in baseline trials where no probe pattern was presented. These results suggest that serial dependence is modulated by the informational worth of perceiving.

2. Methods

2.1. Participants

Seventy-four observers (45 female) took part in this experiment (mean age = 20.56 ± 4.04). All had normal or corrected-to-normal vision. Informed consent was obtained from all individual observers.

2.2. Stimuli and apparatus

The task was coded in the PsychoPy 2021.1.2. environment (Pierce et al., 2019) and ran on a 120Hz refresh rate 1920x1080 monitor with brightness kept constant across observers. Subjects were seated approximately 50 cm away from the monitor.

Stimuli were visual patterns created by connecting dots on a 5x5 white-background grid. In this experiment, we created 3 separate categories of visual patterns (Figure 1) by varying their structure from “most structured” to “random”. Different categories were created by following distinct rules for pattern formation. The least random category which we term “highly structured” was created by drawing various easily recognizable geometrical shapes. A second, “structured” category did not include recognizable shapes but still followed the rule that all lines on the grid must be serially connected. Lastly, random patterns were created via MATLAB code such that lines were randomly placed on the grid. Random patterns did not follow any specific rule other than the fact that each line connected 2 dots by necessity. All stimuli, regardless of structure category, had the same number of line connections.

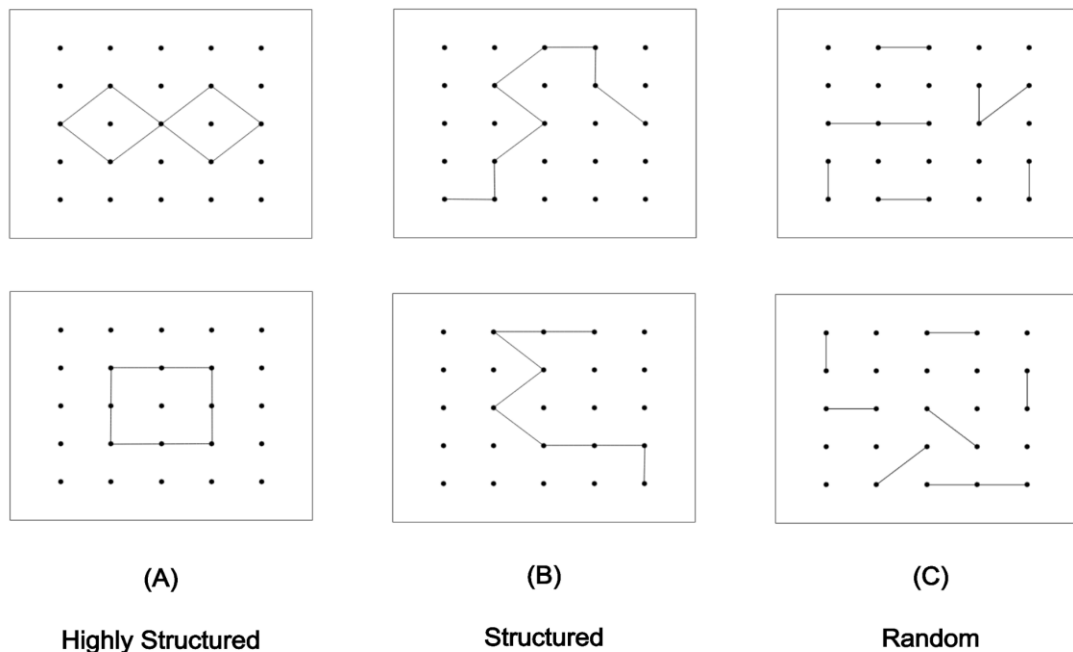


Figure 1. Types of stimuli. All stimuli were created by connecting dots on a 5x5 grid. Highly structured patterns were generated by manually creating various generic geometrical shapes. To create structured patterns, individual lines on the grid always had to form a connected pattern, thus still following a rule without forming recognizable shapes. By contrast, random patterns were random-number-generated and did not involve artificially imposed rules or any sort of manual intervention, other than the fact that a line always had to connect 2 dots on the grid.

2.3. Task and procedure

The current experimental design differs substantially from standard serial dependence tasks in perception. Rather than investigating temporal biases in the perception of low-level features, we have employed a task where the beneficial effects of continuity fields can be quantified in terms of decision-making accuracy. In addition, we do not require a decision for the probe stimuli (e.g., Aguilar-Lleyda et al., 2021) in order to rule out both decisional serial dependence and response priming interpretations. In other words, this design is specifically constrained to investigating the effects of visual perception on subsequent memory.

At the beginning of the experiment, subjects were familiarized with 2 visual patterns (one structured and one random) which they were instructed to remember as best as they could. Subjects were left as much time as they needed to remember each pattern. They were told that they would participate in a recognition memory task where they would encounter unseen-before patterns among the 2 patterns they were instructed to remember. Each time a pattern is presented, they would have to indicate whether the presented pattern was one of the trained patterns or not by pressing the left arrow key (trained) or the right arrow key (novel) on the keyboard. Subjects were instructed to use the index and middle fingers of their dominant hand.

Each observer completed 200 trials, 50 of which included one of the trained stimuli (making for 100 “trained” trials in total). We created 50 different visual patterns per stimulus category for the probe stimuli (resulting in 150 probe stimuli). Similarly, half of the trials presented a novel target pattern (resulting in 102 target stimuli in total), where two patterns served as the trained stimuli. Each trial began with a 350-500 ms fixation cross presented in the middle of the screen. The duration of the fixation was randomly sampled from a uniform distribution of durations. Next, a probe pattern appeared for 33.3 ms (an equivalent of 2 frames

on a 60 Hz monitor) and was immediately masked by visual noise created specifically for our type of stimuli. The mask was presented for 66.4 ms (double the amount of the probe pattern, or 4 frames on a 60 Hz monitor). Then, the target pattern was presented and stayed on the screen until a decision was made. A random ITI between 2500 and 3500 ms separated trials (sampled from a uniform distribution). An example trial can be seen in Figure 2.

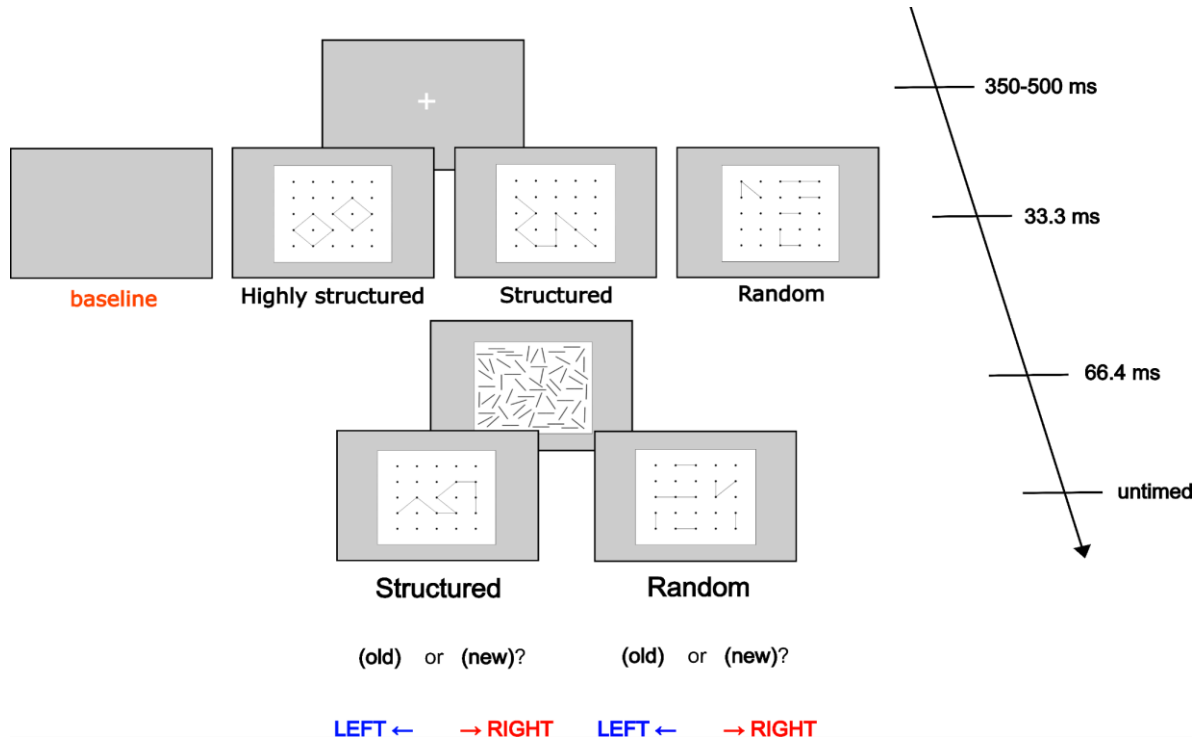


Figure 2. An example trial. A fixation cross was presented in the center of the screen for a duration between 350 and 500 ms sampled from a uniform distribution. Then, a probe pattern was presented for 33.3 ms (2 frames on a calibrated 60 Hz monitor). In some (baseline) trials, no probe pattern was presented, leaving a blank 33.3 ms interval, thereby preserving the usual trial structure. The probe pattern was immediately masked for 66.4 ms (4 frames). After the mask presentation had ended, a target pattern appeared on the screen for an unlimited amount of time. The observer's task was to indicate whether the pattern was a stimulus they had to remember by pressing the left arrow key (old) or the right arrow key (new) on the keyboard. Subjects were instructed to make decisions as fast as possible. All observers were trained on 2 patterns (one structured and one random), where each pattern appeared with equal probability throughout the experiment.

In contrast to probe patterns, target patterns could only be structured or random. Highly structured patterns were not used as target stimuli to avoid making the task too easy. Subjects were not in any way instructed about the presentation of the probe patterns.

2.3.1. Practice trials

Each observer went through 20 practice trials, 10 of which included one of the two trained patterns. Practice trials were meant to train subjects on the 2 critical patterns and assess the detectability of the probes. The structure of practice trials was identical to a regular trial structure. Subjects had to achieve a mean accuracy of 90% to proceed with the actual experiment. If a 90% accuracy was not achieved on the first try, the practice block restarted. Failure to meet the criterion from the second try resulted in ending the experiment.

After subjects had made their recognition memory decision in a trial, two incorrect patterns along with the real probe pattern appeared on the screen in randomized order (Figure 3). Subjects were instructed to indicate which one of those patterns was briefly presented before the pattern they had to attend to. One-sample t-tests later revealed that average performance across observers was significantly different from chance level for all structure levels - $t(67) = -7.8$, $p = 5.52 \times 10^{-11}$, Cohen's $d = -0.94$ (highly structured), $t(67) = 2.92$, $p = 4.74 \times 10^{-3}$, Cohen's $d = 0.35$ (structured), $t(67) = 1.44$, $p = 1.44 \times 10^{-5}$, Cohen's $d = 0.56$ (random).

Accuracy in forced-choice identification of the masked probe pattern

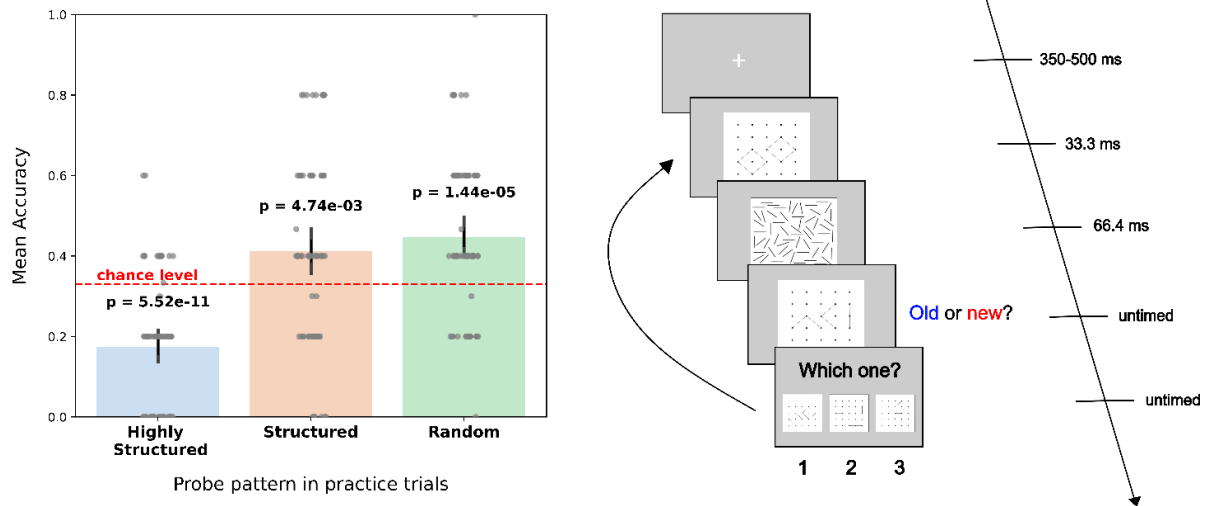


Figure 3. Awareness check in practice trials. We wanted to measure the degree to which observers could detect probe patterns. After a memory decision was made, we required observers to identify the current probe among 2 other patterns (a 3-choice identification). As evident, individual observers varied substantially in the degree to which they obtained conscious awareness of the briefly presented probe. Regardless, all one-sample t-tests were highly significant, suggesting that on average observers had above-chance signal discrimination for the probe pattern, regardless of the degree of structure in the stimulus. Error bars represent 1 standard error (SE).

As evident, performance in practice trials where a highly structured probe was presented was very significantly different from chance level. However, the effect was in the opposite direction, suggesting a systematic bias against choosing the correct option in the detectability task whenever a highly structured probe was presented. This result can be easily explained with the fact that our target patterns did not include a highly structured category. Hence, when subjects' signal detection of the probe pattern was just below or at their threshold, they were more likely to select either one of the two options that more closely resembled the patterns they could actually see (the target patterns that required a recognition memory decision). In other words, these results are a symptom of guessing performance between the structured and the random options. Nevertheless, the mean accuracies of 41% and 44% for the structured and the

random probes, respectively, confirm that subjects had at least some detection of the probes, which serves as foundation for the main analyses.

2.4. Data and code availability

All raw data and analysis code are openly available at <https://doi.org/10.17605/OSF.IO/PRMEA>.

3. Results

3.1. Analyses

Six observers were dropped from the analysis for failing to surpass the practice (training) phase of the experiment where a 90% mean accuracy in the recognition memory task was required in order to proceed. In addition, all trials of -2.5 or +2.5 standard deviations away from the response time mean for each participant were omitted (3.5% of trials). First, we used a repeated measures ANOVA to assess the effect of target pattern structure and probe pattern structure on sensitivity (d') during the recognition memory task. Then, we used Bonferroni-corrected pairwise comparisons to look for differences on the main effect and interaction level. The most important analysis was the repeated measures ANOVA we ran for the response times in each condition. Once again, we controlled for both types of stimuli (target and probe patterns) and their interaction term. We then compared response times using Bonferroni-corrected pairwise comparisons.

3.2. Manipulation checks

Mean accuracies for the two trained target patterns were equal to 98.4% ($SD = \pm 12\%$) for structured and 97.5% ($SD = \pm 15\%$) for random. Mean response times were equal to 911 ms ($SD = \pm 53$) and 902 ms ($SD = \pm 50$), respectively. Novel structured patterns had a mean accuracy of 99.5% ($SD = \pm 6\%$), and novel random patterns had a mean accuracy of 99.8% (SD

= $\pm 3\%$). Mean response times were 804 ms ($SD \pm 33$) and 794 ms ($SD \pm 31$), respectively. As evident, our recognition memory task was incredibly easy.

First, we checked whether performance in the recognition memory task differed depending on the type of target pattern. We performed a repeated-measures ANOVA on response accuracy ($F(3, 201) = 3.9$, $p = 0.009$, $\eta_p^2 = 0.05$). Pairwise comparisons by the method of Bonferroni revealed that the only significant difference was between the trained structured pattern and novel random patterns ($t(67) = 3.17$, $p = 0.01$, Cohen's $d = 0.57$), where novel random patterns yielded higher accuracy on average. Importantly, the two trained patterns (structured and random) did not differ from each other ($t(67) = 0.86$, $p > 0.9$).

3.3. Sensitivity (d') and response times in the memory task

The critical result in this experiment was the effect of probe patterns on sensitivity (d') and reaction times during the recognition memory task. Sensitivity (d') was a control measure in the sense that if any effects were to be significant, this would most likely mean that observers were prone to mistaking the probe for the target pattern. A potential difference between probe pattern conditions would still be uninteresting due to the discrepancy between probe pattern types and target pattern types. Namely, since we lack a “highly structured” target category, observers would be more likely to mistake structured and random probes for the target stimulus, resulting in lower sensitivities for the structured and random probe conditions. In that sense, our main dependent measure for assessing differences in decisional processing was the response time across conditions while controlling for incorrect decisions.

Indeed, probe patterns had no effect on sensitivity - $F(3, 201) = 1.595$, $p = 0.191$, despite observers having at least partial detectability of them. However, response times across probe pattern conditions differed substantially - $F(3, 201) = 6.784$, $p = .0002$, $\eta_p^2 = 0.09$ (Figure 4)

(based on 96.5% of trials). Specifically, response times in our structured condition were significantly faster relative to our baseline (no probe) condition - $t(67) = 4.032$, $p = 0.0008$, Cohen's $d = 0.16$. None of the other probe conditions differed from the baseline condition where no probe was presented.

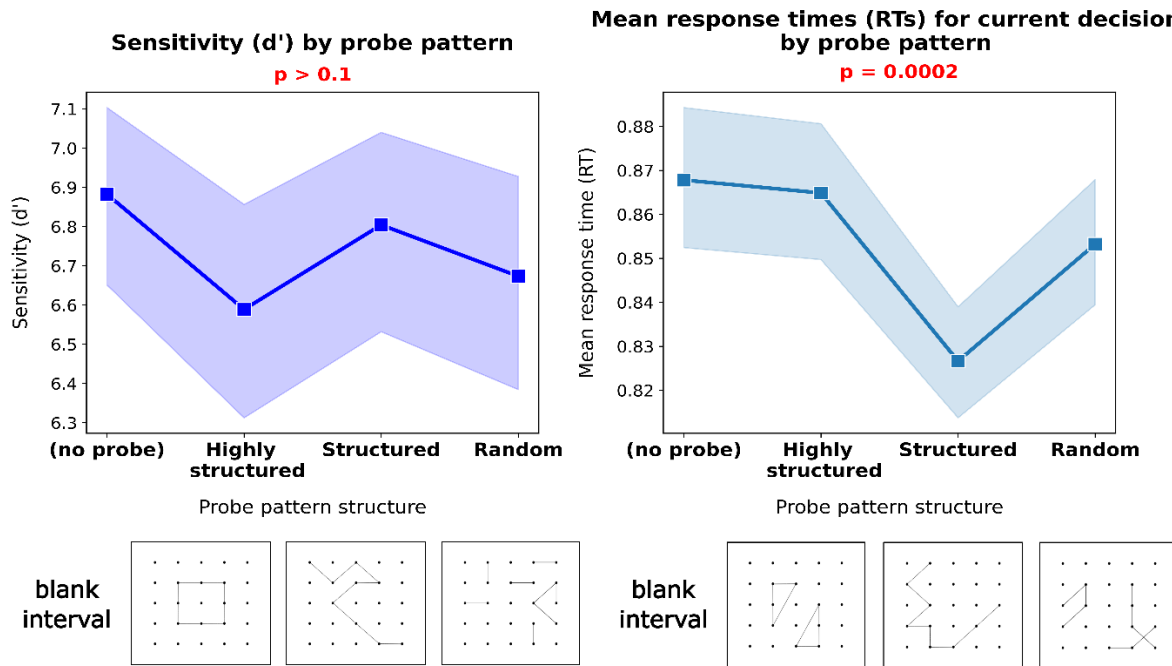


Figure 4. Sensitivity (d') and response times in recognition memory decisions per probe pattern. None of the probe pattern conditions differed significantly from the baseline (no probe) condition, suggesting that observers' signal discrimination of the target was not impaired by the presentation of the probe patterns ($p > 0.1$). By contrast, the amount of structure in probe patterns had a significant effect on reaction times during the recognition memory task ($p = .00002$). Namely, response times in structured trials were significantly faster than response times in baseline trials. Simultaneously, response times in baseline trials did not differ from any other condition. Error bars represent 1 standard error (SE).

In addition, highly structured probe patterns differed from structured probe patterns ($t(67) = 3.36$, $p = 0.007$, Cohen's $d = 0.15$). However, this effect provides no further insights since highly structured probe patterns did not differ from our baseline condition ($t(67) = 0.35$, $p > 0.9$). Similarly, random probe patterns differed from our structured probe patterns ($t(67) = 3.07$, $p = 0.01$, Cohen's $d = 0.11$), but did not differ from the baseline condition ($t(67) = 1.37$, $p >$

0.9). This proves that the only effect of interest is the difference between response times in the baseline and structured conditions.

In order to better assess the nature of this effect, we performed separate ANOVAs for response times within different types of memory decisions. Namely, we were interested in how decision response times differed whenever a correct response was given (a hit or a correct rejection). Once again, this is crucial in order to rule out the possibility that our results are a symptom of an attentional or interference process where structured probe patterns induced faster (but incorrect) response times during the memory task. In addition, any potential difference between the general trend in response times across signal detection outcomes would yield a better understanding of the process underlying this effect. Response times per condition for hit and correct rejection trials can be seen in Figure 5.

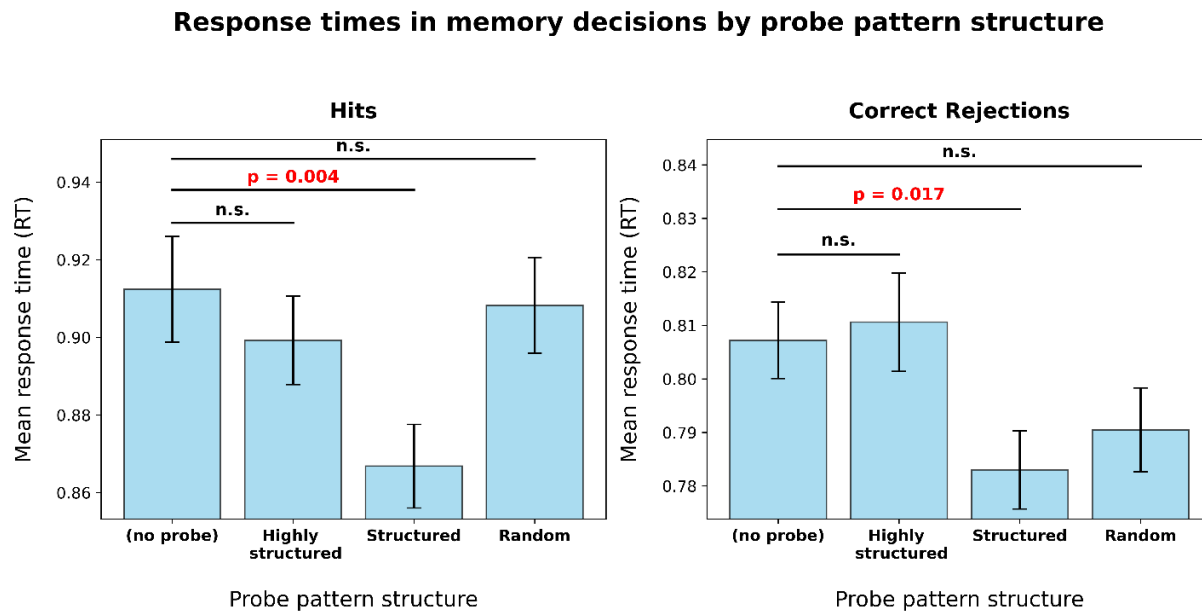


Figure 5. Response times in recognition memory decisions by probe pattern and type of correct response. Response times in the structured probe condition were significantly faster relative to baseline for both types of correct memory decisions (hits and correct rejections). Once again, all other comparisons were insignificant relative to baseline. Error bars represent 1 standard error (SE).

As evident, the effect is present in trials where subjects gave correct responses. Specifically, responses in structured trials were significantly faster than responses in baseline trials whenever the response was a hit ($t(67) = 2.842$, $p = 0.004$, Cohen's $d = 0.07$) or a correct rejection ($t(67) = 2.379$, $p = 0.017$, Cohen's $d = 0.05$). Once again, response times in the baseline condition did not differ from any other condition. By necessity, this means that our structured probe patterns prompted faster memory decisions, and not that our highly structured and random patterns prompted slower memory decisions. If that were to be the case, response times in highly structured and random trials would have been slower compared to trials where no probe pattern was presented. This proves our point that the effect at hand is not a symptom of interference.

3.4. Effect of target structure on decision response times

Lastly, we were interested in a potential interaction between the amount of structure in the probe and the target stimulus. We first separated target patterns by “structured” and “random”, irrespective of pattern novelty (trained vs. novel). Then, we fit a repeated-measures ANOVA with the newly grouped target factor, probe patterns, and the interaction between targets and probes. However, the interaction was insignificant ($p > 0.9$). In addition, target pattern structure had no effect on response times ($p > 0.4$). Lastly, we checked for an interaction between target novelty (old vs. new) and probe pattern structure. This effect did not reach significance either ($p > 0.3$). An interaction plot between target structure, irrespective of target novelty, and probe structure can be seen in Figure 6.

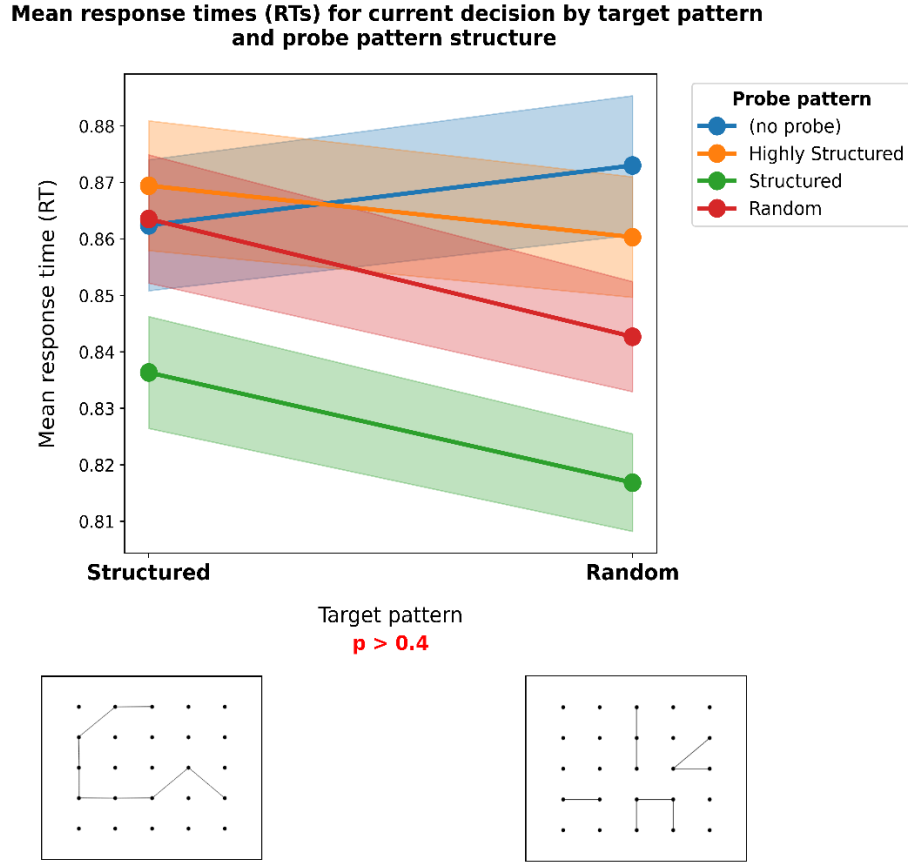


Figure 6. Response times in recognition memory decisions by probe pattern and target pattern structure simultaneously. There was no significant difference in response times as a function of target type ($p > 0.4$), regardless of what seemed to be a trend for structured targets to elicit slower responses. The interaction between target pattern structure and probe pattern structure was also insignificant ($p > 0.9$). Error bars represent 1 standard error (SE).

4. Discussion

We argued that the strength of serial dependence is modulated by basic structure in the environment. Specifically, we proposed that increasing the amount of structural disorder and randomness in stimuli would reduce their informativeness, thereby reducing the strength of their impact on future perception and decisions. To test this prediction, we created a recognition memory task where subjects had to discriminate between trained and novel visual patterns whose randomness was systematically varied. In addition, we presented a probe visual pattern that

immediately preceded the target stimulus and did not require a decision itself. We found that subjects made faster (and correct) decisions in the recognition memory task whenever the target pattern was preceded by a probe pattern that was neither fully structured nor fully random - what we call an “optimal” amount of structure in a stimulus. Conversely, both fully structured and random patterns had no effect on future decision-making. We will refer to the key stimulus category as “optimal” to highlight its two major qualities: 1) its informational importance as opposed to the other two categories, reflected by its effect on memory decisions; 2) the efficient nature of this effect, reflected by its direction, namely – its facilitatory impact on future decision-making.

One possible interpretation of these results would be attentional. That is, it could be argued that our “optimally” structured patterns attracted more attention than other patterns and therefore elicited a stronger effect on memory decisions. In the same way, it could be argued that our highly structured and random probe patterns were simply ignored, thereby failing to elicit an effect. However, both interpretations disregard the crucial finding that the effect of “optimal” stimuli occurred in correct memory decisions and that the effect was facilitatory, rather than interferitory. Specifically, a tendency to ignore one type of stimulus and attend to a different type of stimulus would result in slower, rather than faster, response times for the stimulus that was attended. In addition, we can be positive that what we interpret as a facilitatory effect is not in fact baseline since the effect occurred relative to a control condition where no probe pattern was presented. Hence, it also could not be claimed that highly structured and random stimuli interfered with decision-making since neither sensitivity (d') nor response times differed from our control (baseline) condition where no probe was presented.

Rather, we propose an efficient coding account for these results (Attneave, 1954; Barlow, 1961). Efficient coding applies the informational concept of redundancy (Shannon, 1948) to visual perception. Specifically, it proposes a bottom-up selection process where surprising stimuli (i.e., more informative stimuli) have a priority over highly predictable (i.e., generic) stimuli. This concept stems from the idea that the cognitive system is an active seeker of informational gain in the form of novel and “surprising” information. Hence, both too much structure and a complete lack of structure would be deemed irrelevant due to informational redundancy (Barlow, 1961). Moreover, classic efficient coding suggests that this process manifests at very early stages of visual processing, prior to attentional allocation. However, what efficient coding doesn’t suggest is that an optimal ratio of structure and disorder might have a positive (in the sense of facilitatory) effect on further processing.

Indeed, previous work on serial dependence has shown that attractive biases toward previous information can be modulated by violating stimulus expectations and thereby manipulating the amount of surprise associated with stimulus sequences (Abreo et al., 2023). However, such an interpretation of surprise treats randomness as a matter of the relative frequency of a stimulus in a given context, rather than a matter of structural coherence. In addition, varying stimulus expectations incorporates higher-level cognitive factors, some of which might include attentional allocation. Whether or not we choose to disregard attention as a possible influence, our results fit very well with Cicchini’s suggestion of a functional advantage of serial dependence where serial effects promote faster response times (Cicchini et al., 2018). Again, this interpretation is quite contrary to an attentional hypothesis where attending to a preceding stimulus would result in slower responses.

Regardless, what becomes apparent is that there seems to be a qualitative difference between sensory noise induced by varying stimulus statistics or visibility, and noise induced by varying the structural disorder of stimuli. Namely, while there is a positive relationship between sensory noise and serial dependence (Gallagher & Benton, 2022; Kim & Alais, 2021; Gallagher, 2023; Manassi et al., 2018), noisy observations tend to deteriorate, rather than inform, subsequent processing. With our results, this is simply not the case. In addition, our results reveal a non-linear trend with regard to the influence of structural disorder. That is, if structural disorder is grasped as a continuum, only a certain fraction of this continuum exhibits a serial dependence effect. With sensory noise, on the other hand, serial dependence strength increases steadily, such that higher uncertainty (noise) is associated with stronger serial dependence. Moreover, we are currently not aware of any work to have shown how any type of noise (sensory or else) induced by varying stimulus parameters might impact subsequent memory decisions in a desirable and informative manner.

In the present work, we showed that the amount of structure in the visual environment might impact the processing time needed to arrive at a future memory decision. Surprisingly, the impact of structure on response times was not linear. Rather, our results suggest that a certain ratio of structure and disorder facilitates the ease with which future decisions are made. We interpreted this result in light of the efficient coding framework which suggests that the higher and the lower asymptotes of structure in visual experiences fail to inform future processing due to informational redundancy. Interestingly, the effect transfers from the perceptual to the memory domain, and offers yet another glimpse into the way that cognitive and perceptual experiences are not purely influenced, but also informed by recent perception. Crucially, neither

serial dependence nor efficient coding work has suggested that some optimal amount of structure-disorder ratio should increase, rather than deteriorate, cognitive efficiency.

Ethics

This research has been approved by Sofia University's Ethics Committee (95-M-20 #3/06.04.2023).

Conflict of interest

We declare no competing interests.

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Data accessibility

All data and code related to this project are available at
<https://doi.org/10.17605/OSF.IO/PRMEA>.

Declaration of AI use

AI was used solely as a coding assistant for visualization code.

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