Cognition 174 (2018) 19–27

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/cognit

Adding statistical regularity results in a global slowdown in visual search

Anna Vaskevich[a,*], Roy Luria[a,b]

[a] School of Psychological Sciences, Tel Aviv University, Tel Aviv 6997801, Israel
[b] Sagol School of Neuroscience, Tel Aviv University, Tel Aviv 6997801, Israel

ARTICLE INFO

Keywords:
Statistical learning
Implicit learning
Practice
Visual search
Predictive value

ABSTRACT

Current statistical learning theories predict that embedding implicit regularities within a task should further improve online performance, beyond general practice. We challenged this assumption by contrasting performance in a visual search task containing either a consistent-mapping (regularity) condition, a random-mapping condition, or both conditions, mixed. Surprisingly, performance in a random visual search, without any regularity, was better than performance in a mixed design search that contained a beneficial regularity. This result was replicated using different stimuli and different regularities, suggesting that mixing consistent and random conditions leads to an overall slowing down of performance. Relying on the predictive-processing framework, we suggest that this global detrimental effect depends on the validity of the regularity: when its predictive value is low, as it is in the case of a mixed design, reliance on *all* prior information is reduced, resulting in a general slowdown. Our results suggest that our cognitive system does not maximize speed, but rather continues to gather and implement statistical information at the expense of a possible slowdown in performance.

1. Introduction

Since the pioneering work of Reber (1967), a large body of evidence has accumulated regarding our ability to pick up regularities from the environment. This evidence comes from primarily two fields- statistical learning and implicit learning. Although the two fields rely on different learning paradigms, the general objective is similar: to explore our ability to extract and use regularities from the environment (for a review see, Perruchet & Pacton, 2006). Most of the studies conducted so far have focused on the following questions: What types of regularities can be acquired (Cohen, Ivry, & Keele, 1990; Fiser & Aslin, 2002; Pothos, 2007), under which conditions regularities are identified (Turk-Browne, Jungé, & Scholl, 2005), and how implicit is this learning process (Bertels, Franco, & Destrebecqz, 2012). The results suggest that both visual and auditory regularities can be acquired (Frost, Armstrong, Siegelman, & Christiansen, 2015), and that the extraction and use of these regularities can occur incidentally and implicitly, so that the observer is unaware of the learning (Bertels et al., 2012; Buchner & Wippich, 1998).

One important aspect of implicit learning of regularities is how it affects performance. Here, it is important to separate effects regularity may have on performance in the task in which it is embedded (i.e., ongoing performance) from effects regularity may have on performance in subsequent tasks. When it comes to the impact regularity has on subsequent tasks, both facilitating and interfering effects have been demonstrated. For instance, Otsuka and Saiki (2016) showed that objects that were previously encountered in structured sequences were remembered better than objects from random sequences, while distractor items that were inserted into random sequences were remembered better than those inserted into structured sequences. Regarding ongoing performance, interference effects originating from an additional regularity that was not beneficial to the task, were found in a task that required summary statistics (Zhao, Ngo, McKendrick, & Turk-Browne, 2011; Zhao & Yu, 2016). This type of interference may be caused by a competition between two statistical operations – statistical learning and summary statistics (Zhao et al., 2011).

In the present work, we focused on the impact regularity may have on online performance from a different perspective: we tested the impact of a single, potentially beneficial regularity on general practice effects. We define practice effects as faster Reaction Times (RTs) and/or higher accuracies that are a result of repeatedly performing the task, without the presence of any regularity. For instance, in sequence learning tasks (Cohen et al., 1990), or visual search tasks (Clark, Appelbaum, van den Berg, Mitroff, & Woldorff, 2015), participants become faster as the task progresses without the presence of regularity. Current statistical learning theories suggest that introducing regularity that is relevant to the task should result in even better performance as the regularity contains additional beneficial information (Goujon, Didierjean, & Thorpe, 2015; Perruchet & Pacton, 2006).

While this assumption seems to be obvious, we argue that the

* Corresponding author.
E-mail address: annav@mail.tau.ac.il (A. Vaskevich).

https://doi.org/10.1016/j.cognition.2018.01.010
Received 5 July 2017; Received in revised form 22 January 2018; Accepted 23 January 2018
0010-0277/ © 2018 Elsevier B.V. All rights reserved.

relationship between general practice and learning with regularity was never properly assessed. This is because current statistical learning paradigms that assess online performance lack the necessary baseline conditions reflecting only practice effects (Chun & Jiang, 1998). Such conditions are necessary in order to evaluate separately performance in a task with and without regularity. To overcome these limitations, we rely on a task in which practice performance can be assessed both in the presence and absence of regularity – visual search (Wolfe, 1998). We now turn to describe this paradigm and how performance was measured in the present work.

In a visual search task, participants search for a predefined target stimulus among distractors and are asked to respond as fast as possible (Wolfe, 1998). Typically, participants become faster to find the target as the task progresses (Sireteanu & Rettenbach, 1995). A recent ERP study suggested that this general task improvement (i.e., practice) is a result of modulations of several processing stages that involve early attentional processes, target discrimination processes and response selection (Clark et al., 2015). Together, these results show that while executing the task, there is an ongoing updating of task-set parameters that leads to a gradual improvement in performance. We consider the gradual improvement in performance in such tasks to result from practice alone because it is achieved under conditions that do not involve any regularity.

The effect of embedding regularities in a visual search task is investigated by mixing a consistent mapping condition with a random mapping condition (Chun, 2000; Chun & Jiang, 1998). In the consistent mapping condition, the target is embedded in an invariant configuration that is repeated across the experiment, while in the random mapping condition the target appears in a novel or unrepeated configuration. Participants are faster to find the target in the consistent mapping condition than in the random mapping condition, an effect termed "contextual cueing" (Chun & Jiang, 1998). Because this effect occurs without instructions, without an intention to learn, and without evidence of conscious memory, it is thought to result from implicit learning (Chun & Jiang, 2003; but see also Vadillo, Konstantinidis, & Shanks, 2016). To date, the contextual cueing effect has been replicated numerous times (for a recent review see Goujon et al., 2015). A widely accepted interpretation of this effect is that the repeating context in the consistent mapping condition is learned implicitly and serves as a cue that guides attention to the target (Chun, 2000; Harris & Remington, 2017; Peterson & Kramer, 2001; but see also, Kunar, Flusberg, Horowitz, & Wolfe, 2007; Schankin & Schubö, 2009).

Given this interpretation of the contextual cueing effect, it is reasonable to assume that the implicit learning of regularities operates in accordance with practice effects. However, we argue that such a conclusion is premature, because within this paradigm the consistent and random conditions are mixed. As such, performance in the random condition cannot be regarded as a pure baseline that reflects only practice effects. Instead, performance in this condition is driven by general practice in a task that also contains regularity (i.e., affected by the consistent mapping condition). Similarly, the consistent mapping condition reflects a situation in which the regularity is diluted by random trials. In order to separate and compare practice performance in a task with and without regularity, which is the aim of the present work, it is essential that performance in the mixed design be contrasted with additional baseline conditions that reflect general improvement alone (i.e., no regularity in the task), and improvement in a task with regularity that is valid on all trials. Employing the above described baseline conditions should allow us to determine whether the presence of regularity drives performance beyond practice.

Importantly, adding these baseline conditions will also allow us to evaluate the influence of regularity on online performance from a predictive value perspective. We define predictive value as the extent to which incoming information is consistent with the system's expectations. In the decision-making domain, it is well established that multiple sources of information, such as the history of items and the current visual input are reconciled according to their predictive values and influence the decision on a given trial (Behrens, Woolrich, Walton, & Rushworth, 2007). The impact of validity has also been demonstrated in statistical learning (Kim, Lewis-Peacock, Norman, & Turk-Browne, 2014): items that were first encountered in a specific context, which was then changed, were more likely to be forgotten than items that appeared in an unchanged context. Presumably, when a previously experienced context is reencountered, a prediction about which item should appear in that context is automatically generated. If this information proves to be invalid, and the expected item does not appear, the representation of the item in memory may become vulnerable (Kim et al., 2014).

The above described study shows how validity of statistical information may affect a consequent memory task. However, according to the predictive value framework, the reliability of information changes during the acquisition task itself, so that the values of the incoming information is constantly reassessed and updated (Behrens et al., 2007). The recently proposed predictive-processing framework, argues that similar processes operate during perception (Clark, 2013; Lupyan, 2015; Lupyan & Clark, 2015). Within this framework the cognitive system is viewed as a probabilistic-prediction system that is continuously estimating and re-estimating its own sensory uncertainty, assigning differential weights to the systems' expectations (i.e., previous experience) versus the current inputs. In other words, the influence of what the system "knows" changes according to the reliability of the incoming information. This adaptive process is described as 'variable precision weighting': a mechanism for tuning the extent to which input is modulated by top-down predictions (A. Clark, 2013; Lupyan, 2015; Lupyan & Clark, 2015). Thus, according to the predictive-processing framework, a task that contains information with low predictive value should lead to a general slowdown.

Relying on the predictive-processing framework, and previous results from statistical learning (Kim et al., 2014), we argue that when regularity is present in the task, the predictive value of the regularity may be crucial, because it determines the extent to which all prior information is taken into consideration. When the regularity applies to all trials in the task the predictive value is high. Counter intuitively, when the task contains no regularity, the predictive value is also high (i.e., no regularity is expected). When the regularity applies to half of the trials, its predictive value is relatively low. Thus, mixing consistent mapping with random trials should result in interference and in slower responses because the incoming information is valid only on 50% of the trials.

2. Experiment 1

In the present study, three groups of participants completed a visual search task that was either random (i.e., without any regularity), completely structured, in which case the regularity was valid on every trial (i.e., consistent mapping), or a visual search with consistent and random mapping conditions mixed.

The key aspect of performance that was assessed is the end-of-session performance. This measurement represents the best performance (i.e., fastest RTs) that is achieved in a given session, and is ideal for our current purpose because it reflects both practice effect and the size of the contextual cueing effect. Several previous studies have successfully used end-of-session performance to estimate the size of the contextual cueing effect across conditions (Chun & Jiang, 1998; Kunar, Flusberg, & Wolfe, 2006; Kunar, Flusberg, & Wolfe, 2008) and experiments (Chun & Jiang, 1998).

Current statistical learning theories predict that the best performance would be observed in the consistent mapping group, when the regularity is present on every trial. Performance in the mixed design group should be worse than in the consistent mapping group because the regularity is present on only half of the trials. Lastly, the worst performance is expected to appear in the random group, as it contains no beneficial regularity. Alternatively, from the perspective of the predictive-processing theory (Clark, 2013), performance in the mixed design group is expected to be the worse. This is because the regularity in a mixed design is unreliable, and therefore should lead to reduced reliance on all prior knowledge.

2.1. Method

Participants. Most contextual cueing studies rely on sample size of 12–17 subjects (Chun & Jiang, 1998; Chun & Jiang, 1999; Harris & Remington, 2017; Kunar et al., 2007). As we rely on a between-subject experimental design we doubled this number for each group. Ninety-three undergraduate students (77 females, mean age 23, $SD = 2.4$) from Tel Aviv University participated in the study in return for credits or payment. There were no differences in age or gender between the three experimental groups. Three participants that exhibited very low accuracy rates (see results) were discarded from further analyses. All analyses are reported for the remaining ninety participants.

2.1.1. Stimuli and procedure

All participants gave informed consent following the procedures of a protocol approved by the Ethics Committee at the Tel Aviv University. Participants then completed three tasks in the following order: visual working memory (VWM) capacity assessment, visual search task and a forced-choice recognition test. The VWM capacity estimation was done with a change detection task (Luck & Vogel, 1997; Luria & Vogel, 2011). All tasks were conducted on a 23-inch light emitting diode monitor with a 120 Hz refresh rate, using 1920 × 1080 resolution graphics mode.

Stimuli in the visual search task were white T's and L's. All stimuli were made up of two lines of equal length (forming either an L or a T). From a viewing distance of approximately 60 cm, each item in the display subtended 1° × 1° of visual angle. For the L letter, the vertical bar was offset towards the center by 0.1° (Fig. 1). All items appeared within an imaginary rectangle (25° × 20°) on a black background with a white fixation cross in the middle of the screen (0.4° × 0.4°). Stimuli in the change detection task (VWM estimation) were colorful squares that were chosen randomly on each trial from a set of nine colors: blue, brown, cyan, green, orange, pink, red, and yellow. Each square subtended approximately 1.2° × 1.2° of visual angle and was randomly positioned within a 20° × 20° region upon a grey background. The minimal distance between each two stimuli was 2.1° of visual angle (center to center).

Visual Working Memory. VWM capacity estimation was done with a change detection task: arrays of either four or eight colored squares (memory array) appearing for 150 ms followed by a 900 ms retention interval after which one colored square (test probe) was presented at the location of one of the items from the memory array. Participants made an un-speeded keyboard press indicating whether the color of the test probe was the same or different from the color of the original item presented in that location (with equal probability for same and different test probes). Sixty trials were presented for each array size in one intermixed block (120 trials overall). On changed trials, the changed item was replaced with a color not presented in the memory array. VWM capacity was computed with a standard formula: $K = S(H\text{-}F)$. K is the memory capacity, S is the size of the array, H is the observed hit rate and F is the false alarm rate (Pashler, 1988).

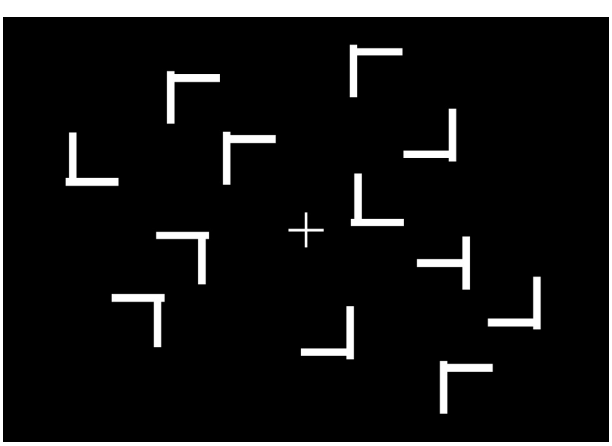

Fig. 1. Visual Search task: The target was a T letter rotated either left or right that appeared among rotated L's (distractors). Participants pressed a response key corresponding to the appropriate target as fast as possible.

Visual search. Participants performed a visual search task looking for rotated T's (target) among heterogeneously rotated L's (distractors). Each trial contained one of two possible targets (left or right rotated T), among eleven distractors. Participants were instructed to press a response key corresponding to the appropriate target as fast as possible. The search display was present on the screen until response. Depending on the group, the visual search contained a consistent mapping condition, a random mapping condition, or both. In the consistent mapping condition, spatial configurations of targets and distractors were randomly generated for each participant (8 layouts for the mixed design group and 16 layouts for the consistent only group). These layouts were then kept constant throughout the task, so that on each trial a target appeared in a predefined location, surrounded by distractors in the specific spatial layout that was paired with the target's location. The order of layouts was randomized in each block. In the random mapping condition targets and distractors appeared in random locations throughout the task (within an imaginary rectangle of 25° × 20°), with the exception that targets could not appear in the same locations as targets from the consistent condition. The minimal possible distance between the center of a target in the consistent and random condition was 2°. In all conditions the identity of the target (left or right rotation) was chosen randomly on each trial and did not correlate with the spatial regularity in any way (Fig. 1).

Participants completed 12 epochs of trials (each epoch was comprised of 4 blocks), so that overall there were 768 trials in the experiment. Every block contained 16 trials. Depending on the group, these were all consistent mapping (i.e., repeating spatial layouts), all random mapping, or 8 consistent and 8 random mapping trials that were presented in a random order. The order of trials in the consistent mapping conditions was randomized between blocks so that the spatial layout was the only regularity in the task.

Explicit memory test. Upon completing the search task participants were asked whether they have noticed any regularity throughout the experiment. Participants then performed a memory test: all spatial layouts were presented in a random order, without targets. For each layout, participants used the mouse to indicate where they thought the corresponding target appeared throughout the task. In order to gain as much insight as possible into any explicit knowledge participants may have, each spatial layout appeared three times.

2.2. Results

All collected data is available through Open Science Framework: https://osf.io/zhyau/. The data was aggregated and organized before the statistical analyses using prepdat (Allon & Luria, 2016).

Visual search. Accuracy was very high for all groups (mixed group: $M = 0.98$, $SD = 0.03$, consistent mapping group: $M = 0.98$, $SD = 0.04$, random mapping group: $M = 0.98$, $SD = 0.01$). Two participants in the mixed design group and one participant in the consistent mapping group exhibited very low accuracy (0.89 > 3 SD from the group mean, 0.86 > 3 SD from the group mean, and 0.77 > 5 SD from the group mean, respectively) and were removed from further analyses. RTs below 100 ms and above 4000 ms (3% excluded), error trials and trials immediately following errors were excluded from further analyses. Removing RTs slower than 4000 ms is in accordance with previous studies that used a task with similar regularity (Chun & Jiang, 1998;

Kunar, Flusberg, & Wolfe, 2006). As in previous studies (Chun & Jiang, 1998; Kunar et al., 2006), data was grouped into twelve epochs, each consisting of four blocks, with each block containing 16 trials of either consistent or random mapping conditions (mixed group), consistent mapping condition only (consistent mapping group) or random mapping only (random mapping group).

To assess the contextual cueing effect in the mixed design group we conducted repeated measures ANOVA with the factors Epoch (1–12) and Condition (consistent mapping/random mapping). There was a significant main effect of Condition ($F(1,29) = 33$, $p < .001$, $\eta_p^2 = 0.53$), with significantly faster RTs for the consistent mapping condition ($M = 1354$, $SD = 225$) than for random mapping condition ($M = 1490$, $SD = 180$), suggesting a contextual cueing effect. There was also a significant main effect of Epoch ($F(11,29) = 88$, $p < .001$, $\eta_p^2 = 0.75$) and a significant interaction between Condition and Epoch ($F(11,319) = 3.2$, $p < .001$, $\eta_p^2 = 0.1$). Further analyses revealed that the consistent condition became significantly faster than the random condition in the fourth epoch, which corresponds to the twelfth presentation of the display ($F(1,29) = 7.8$, $p = .009$), FDR corrected, p value was $p = .01$ (Benjamini & Hochberg, 1995).

End-of-session performance. Following previous studies (Chun & Jiang, 1998; Kunar et al., 2006, Kunar et al., 2008) we collapsed RTs across the last three epochs of the session. This measurement allowed us to evaluate performance at the end of the session, and is typically used to assess the size of the contextual cueing effect. In the mixed design group, we observed the expected contextual cuing effect. The averaged RT in the consistent mapping condition was 1128 ms ($SD = 196$) and 1319 ms ($SD = 218$) in the random mapping condition. The difference between conditions, i.e., the contextual cueing effect was 191 ms ($F(1,29) = 40$, $p < .001$, $\eta_p^2 = 0.58$).

To assess when regularity drives performance beyond general task improvement, we then compared the end-of-session performance between the mixed ($M = 1293$, $SD = 191$) and random ($M = 1123$, $SD = 184$) groups. The effect was significant ($F(1,58) = 4$, $p = .047$, $\eta_p^2 = 0.07$), meaning that the end-of-session performance in the random group was faster than performance in the mixed design group, even though the later contained a potentially beneficial regularity. This result supports the predictions made by the predictive-processing framework- an unreliable regularity may interfere with performance by reducing reliance on all previously gathered information. In contrast, when the regularity was valid throughout the task, and hence highly reliable (consistent mapping group), performance was faster than in the other two groups ($M = 1025$, $SD = 208$) ($F(1,88) = 11$, $p = .001$, $\eta_p^2 = 0.11$) (Fig. 2).

For completeness we also performed a repeated measures ANOVA with the within factor Epoch (1–12) and between factor Group (mixed design/consistent mapping/ random mapping) that revealed a significant main effect of Epoch ($F(11,87) = 288$, $p < .001$, $\eta_p^2 = 0.78$), and a significant main effect for Group ($F(2,87) = 6.9$, $p = .0016$, $\eta_p^2 = 0.14$). Further analyses revealed that the main effect for Group resulted from the mixed design group performing significantly slower than the consistent mapping group ($p < .001$). The interaction between Group and Epoch was not significant ($F(22,957) = 1.4$, $p = .1$).

Next, we compared the end-of-session performance in the consistent and random only groups with the corresponding condition in the mixed design group: consistent mixed vs. consistent alone and random mixed vs. random alone. The difference between the end-of-session performance in the consistent only group ($M = 1025$, $SD = 208$) and consistent mixed ($M = 1128$, $SD = 196$) was marginally significant $F(1,58) = 3.8$, $p = .056$). The difference between the end-of-session performance in the random only group ($M = 1123$, $SD = 184$) and random mixed ($M = 1320$, $SD = 218$) was significant ($F(1,58) = 13.6$, $p < .001$, $\eta_p^2 = 0.19$). This analysis supports our argument that conditions with and without regularity affect each other when mixed, so that a random condition in a mixed design experiment cannot be regarded as a baseline condition for performance without regularity.

Finally, Note that there was virtually no difference between the end-of-session performance in the consistent mapping condition of the mixed design group and performance in the random mapping only group (a difference of 5 ms). Given the current interpretations of the contextual cueing effect this result is very surprising because even though participants in the mixed design group learned the regularity, it failed to facilitate performance beyond a general improvement in a random visual search task.

Explicit memory test. When asked, two participants in the consistent mapping group reported noticing "something" during the visual search task. However, these participants did not choose the correct location for any of the targets. In the explicit memory test, each layout was presented three times, and for each target, we calculated the distance between the correct location and participants' answer. An answer within a radius of 3° from the center of the target (three times the targets' size) was considered correct. We then employed the most lenient criterion possible, so that a correct answer for even one layout was considered as a possible explicit memory trace. Five participants in the mixed design group and eleven in the consistent mapping group matched this criterion for one layout, and two other participants (one in each group) matched this criterion for two layouts. All results were recalculated while excluding participants that could have some explicit memory (six in the mixed design group and twelve in the consistent mapping group). All reported results remained significant, except the

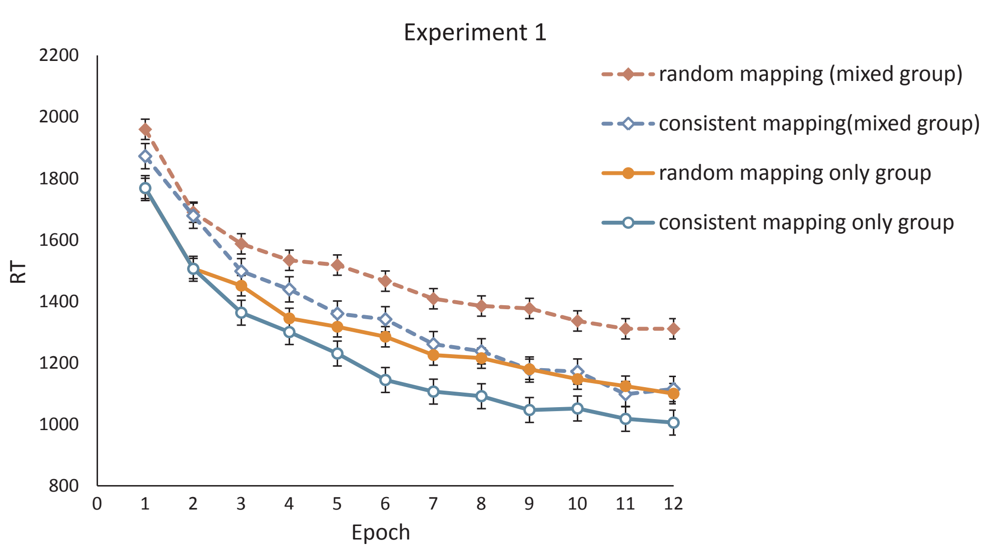

Fig. 2. Results from the visual search task (n = 30 in all groups). RTs are plotted as a function of epochs (4 blocks per. epoch). In the consistent mapping condition targets appeared in the same spatial configuration throughout the task. In the random mapping condition targets and distractors were presented in random locations. A contextual cueing effect was observed in the mixed design group. End-of-session performance was faster in the consistent mapping group than in the other two groups. End-of-session performance in the random group was faster than in the mixed design group.

difference between groups in the end-of-session performance. Participants were no longer faster in the consistent mapping group than in the other two groups ($F(1,58) = 1.02$, $p = .31$).

Visual Working Memory capacity: Mean VWM capacity estimate was as follows: 2.6 ($SD = 0.8$) in the mixed design group, 2.7 ($SD = 0.8$) in the consistent only group, and 2.68 ($SD = 0.8$) in the random only group. There was a significant negative correlation between the VWM estimation and overall RTs in the random visual search group ($r = -0.41 p = .022$). This result is consistent with previous findings: participants with higher WM were shown to react faster in visual search tasks that do not contain regularity (Luria & Vogel, 2011; Shen, McIntosh, & Ryan, 2014; Sobel, Gerrie, Poole, & Kane, 2007; but see also: Kane, Poole, Tuholski, & Engle, 2006). When the visual search included regularity (consistent only and mixed design groups), no correlation with VWM was observed.

2.3. Conclusions (Experiment 1)

In Experiment 1, three groups of participants completed a visual search task with T's and L's as stimuli. The search was either random (random mapping group), structured, in which case the spatial layouts were kept constant throughout the task (consistent mapping group), or a visual search with random and consistent mapping conditions mixed (mixed design group).

The most important result of this experiment is that the end-of-session performance in the random search group was better than the end-of-session performance in the mixed design group. This result is surprising because we know that participants in the mixed design group picked up the regularity- a contextual cueing effect was observed.

Given this pattern of results, it seems that performance in a visual search task with both random and consistent mapping conditions reflects two independent effects. First, there is the facilitating effect of regularity that is illustrated by the difference between the conditions of a mixed design (i.e., the contextual cueing effect). This effect has been demonstrated many times and current models suggest that it stems from facilitation in the consistent mapping condition (Chun, 2000; Chun & Jiang, 1998; Kunar et al., 2008). However, the additional baseline conditions in which consistent and random conditions were administered separately enabled to step out of the beneficial local effect of regularity, and see that the effect was observed under sub-optimal performance, affecting both the random and consistent conditions. We suggest that this general slowdown reflects global interference to general performance. Specifically, we argue that mixing regularity with randomness creates ambiguous conditions, under which the optimization of task-set parameters does not reach its full potential.

We thus argue that the relationship between general practice and learning with regularity is highly dependent on the validity of the regularity. When its predictive value is high, relying on the regularity drives performance beyond general practice effects. However, when the predictive value of the regularity is low, the result is a global interference effect- generally slow performance (relative to performance in a random visual search). Thus, in terms of achieving fast performance, our results imply that it would be better not to look for regularity when it is mixed with random trials. More generally, it suggests that our cognitive system does not maximize speed, but rather continues to gather statistical information from the environment.

The global interference to performance in the mixed design group is shown here for the first time. As such, it is essential to replicate this effect, and to determine whether it is specific to the conditions of Experiment 1. The goal of Experiments 2 was to evaluate the relationship between general practice and learning with regularity, but this time we used images of real objects as stimuli, and a different type of regularity (target-distractors identity pairing instead of a spatial regularity).

3. Experiment 2a-c

The goal of this set of experiments was to examine whether the interference to performance from mixing regularity with randomness can be generalized beyond the specific conditions of Experiment 1. To do so, we manipulated two crucial aspects of the visual search task-stimuli and the type of regularity. First, we used colorful images of real objects as stimuli. This provided us with a very different setting than the black and white T's and L's search in Experiment 1, and enabled us to test the interference effect under relatively naturalistic search conditions. Second, instead of embedding a spatial regularity, we employed regularity between the targets and distractors identities.

To the best of our knowledge, only one study has used images of real objects within a contextual cueing paradigm (Makovski, 2016). In this study, a contextual cueing effect was observed only when both the spatial layouts and the identity of the target and distractors were kept constant. However, it is hard to compare these results with the classic contextual cueing because participants seem to have had explicit knowledge of the regularity (Makovski, 2016).

The regularity in Experiments 2a-c relied on repeated pairings between the identities of targets and distractors. Previous studies have shown that such regularity leads to a contextual cueing effect (Chun & Jiang, 1999; Endo & Takeda, 2004), suggesting it is extracted and influences performance. Theoretically, this effect is considered to rely on the same mechanisms as the spatial regularity contextual cueing (Chun, 2000; Goujon et al., 2015). Therefore, we expected to replicate the effect of low predictive value that was observed in Experiment 1. Namely, mixing regularity with randomness (Experiment 2a) should cause a general slowdown, such that performance will be slower than a completely random visual search condition (Experiment 2b), even though the latter does not contain any regularity.

All the participants in Experiments 2a-c were from the same pool of students and completed the tasks during a single semester. Due to a technical mistake the three groups were ran consecutively, not in parallel. As such, we refer to them as separate experiments.

3.1. Method

Participants. Three groups of participants took part in Experiments 2a-c. All participants were undergraduate students from Tel Aviv University that participated in the study in return for credits or payment. All had normal or corrected-to-normal vision.

Thirty-three subjects (21 females, mean age 24, $SD = 2.3$) participated in Experiment 2a, 33 fresh subjects participated in Experiment 2b (26 females, mean age 24, $SD = 3.5$), and 31 (20 females, mean age 24, $SD = 3.4$) in Experiment 2c. One participant in Experiment 2c with very low accuracy rates (see results) was discarded from the study.

3.1.1. Stimuli and procedure

In all Experiments (2a-c) the procedure was identical to the procedure in Experiment 1. Stimuli in the visual search task were colorful images of real objects (taken from: Brady, Konkle, Alvarez, & Oliva, 2008). From a viewing distance of approximately 60 cm, each item in the display subtended $2.5^\circ \times 2.5^\circ$ of visual angle. All items appeared within an imaginary rectangle ($30^\circ \times 25^\circ$) on a white background with a black fixation cross in the middle of the screen ($0.4^\circ \times 0.4^\circ$).

Visual search. Experiment 2a: similar to the procedure designed by Chun and Jiang (1999), 16 different targets and 80 distractors appeared in the task. The target was defined as a fruit or a vegetable. For each participant, 8 of the 16 targets were randomly assigned to the consistent mapping condition and the other 8 were assigned to the random mapping condition. Similarly, 40 distractors were randomly assigned to each condition. In the consistent mapping condition, distractors were then randomly assigned to sets of five (i.e. distractor-sets). Targets appeared the same amount of times in both conditions. However, in the consistent mapping condition, the target and distractor-set pairing was preserved throughout the experiment. In the random mapping condition, targets and distractors appeared randomly. Each target appeared once in a block. Both the order of the consistent and random trials and the order of targets within the consistent condition were randomized between blocks.

Participants completed eight epochs of trials (each epoch was comprised of 2 blocks). Overall there were 256 trials in Experiment 2a (consistent and random conditions mixed). In Experiments 2b and 2c, for each participant 8 targets and 40 distractors were selected randomly from the pool used in Experiment 2a, resulting in 128 trials. In Experiment 2b the visual search task contained no regularity (random condition only), and in Experiment 2c all targets were paired with distractor-sets (consistent condition only).

Note that this design is different from the design of Experiment 1. First, the present experiments were much shorter- Experiment 2a consisted of 256 trials, while Experiment 1 consisted of 768 trials. The length of the experiment was determined after a pretest revealed that the present task is much easier than the search in Experiment 1. Second, unlike in Experiments 1, we kept the number of trials per condition constant, so that each condition consisted of the same amount of trials whether administered with another condition (mixed design) or alone. This change was made in order to make sure that the differences in Experiment 1 are not a result of differences in the number of trials in each condition- the random and consistent conditions were twice as long as each condition in the mixed design.

On each trial, 11 items (1 target, 10 distractors) were presented in random locations. The 10 distractors were 5 different distractor items (i.e., a set), with each distractor randomly appearing between one to three times on each trial. The task was to search the display and press the space bar immediately upon detecting a target (a fruit or a vegetable). In order to ensure that subjects correctly localized the target, pressing the space bar switched the stimuli to 11 black letters (*A-K*) appearing at all locations used in the search array. Participants were required to type the identity of the letter that occupied the target's location (Fig. 3).

Forced-choice recognition test. When the visual search task contained regularity (Experiment 2a and 2c), participants were tested for traces of explicit knowledge of the regularity. Upon completing the search task participants were asked whether they have noticed that some targets were paired with the same sets of distractors throughout the experiment. They then performed a forced-choice discrimination test: all sets of distractors from the consistent mapping condition were presented in a random order. For each display participants had to choose the target they thought was paired with the display during the search task. The target was chosen from 8 alternatives: 4 targets from the constant mapping condition and 4 from the random mapping conditions (all except the correct target were chosen randomly on each trial). In Experiment 2b, because there was no regularity in the visual search task, an explicit memory test for regularities was irrelevant. Instead, participants were tested for memory of the distractors used in the visual search: 40 pairs, consisting of a distractor image from the visual search task and a new image were presented in a random order. Participants pressed one of two keyboard keys to indicate which image of the pair they had previously seen.

3.2. Results

Visual search. The Overall mean accuracy was very high-Experiment 2a: $M = 0.98$, $SD = 0.05$, Experiment 2b: $M = 0.98$, $SD = 0.02$, Experiment 2c: $M = 0.97$, $SD = 0.03$. In Experiment 2c one participant exhibited very low accuracy (0.87 > 3SD than the group mean) and was removed from further analyses. For all experiments, RTs below 100 ms and above 2000 ms (2.5% or less), error trials and trials immediately following errors were excluded from further analyses. Based on previous studies (Chun & Jiang, 1999), data was grouped into eight epochs, each consisting of two blocks.

In Experiment 2a (mixed design), a repeated measures ANOVA with the factors Epoch (1–8) and Condition (consistent mapping/ random mapping) confirmed the presence of a contextual cueing effect: there was a main effect of Condition ($F(1,32) = 6.6$, $p = .01$, $\eta_p^2 = 0.17$), with faster RTs for the consistent mapping condition ($M = 801$, $SD = 84$) than for random mapping condition ($M = 827$, $SD = 69$). There was also a significant main effect of Epoch ($F(7,32) = 48$, $p < .001$, $\eta_p^2 = 0.6$), reflecting the fact that RTs in both conditions decreased as the task progressed, and a significant interaction between Epoch and Condition ($F(7,224) = 3.3$, $p = .002$, $\eta_p^2 = 0.09$). Further analyses revealed that the consistent condition became significantly faster than the random condition in the second epoch, after three presentations of target and distractors ($F(1,32) = 20$, $p < .001$), FDR corrected p value was $p = .025$ (Benjamini & Hochberg, 1995).

Compared to Experiment 1, the size of the contextual cueing effect was small but significant: the difference between consistent and random conditions collapsed across the last three epochs was 33 ms ($F(1,32) = 6.25$, $p = .02$, $\eta_p^2 = 0.16$), while in Experiment 1 it was

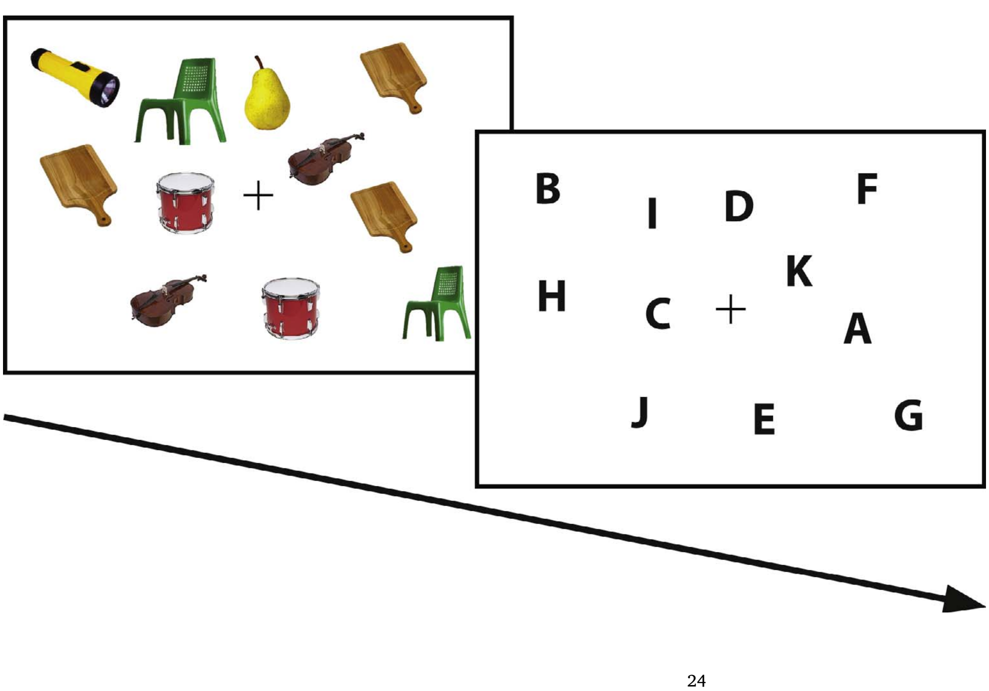

Fig. 3. Visual Search task: The target was either a vegetable or a fruit. Immediately upon detection participants pressed the space bar. The display was then replaced with letters and participants indicated which letter appeared in the target's location.

191 ms. This is probably due to the overall fast RTs that were observed in Experiments 2a-c relative to Experiment 1. Although the fast RTs are consistent with previous studies that used images of real objects in visual search (Makovski, 2016), it seems that under these relatively easy search conditions the potential local benefit that can arise from regularity is minor.

End-of-session performance (Experiment 2a-c). As in Experiment 1, performance was collapsed across the last three epochs of each experiment. We then compared end-of-session performance between experiments.

In order to isolate the effect of mixing regularity with randomness, end-of-session performance in Experiment 2a (mixed design) was contrasted with performance in a visual search task without regularity (Experiment 2b). Replicating the results of Experiment 1, end-of-session performance in the mixed design (Experiment 2a, $M = 765$, $SD = 131$) was slower than performance in a random visual search (Experiment 2b, $M = 655$, $SD = 122$), ($F(1,64) = 12$, $p < .001$, $\eta_p^2 = 0.16$). This result confirms that mixing regularity with randomness results in a global interference to performance.

As in Experiment 1, the end-of-session performance in the consistent mapping only condition ($M = 643$, $SD = 112$), was better than performance in mixed and random conditions collapsed ($M = 709$, $SD = 138$), ($F(1,94) = 5.2$, $p = .025$, $\eta_p^2 = 0.05$). However, unlike in Experiment 1, as can be clearly seen in Fig. 4, this effect was driven by the difference between the mixed and consistent search tasks (Experiment 2a and 2c). Surprisingly, the end-of-session performance in a completely random visual search (Experiment 2b, $M = 655$, $SD = 122$) was as good as performance in the consistent mapping search (Experiment 2c, $M = 643$, $SD = 112$): the difference between the end-of-session performance between these experiments was only 12 ms. Given the overall fast RTs in all the tasks that employed real objects as stimuli (Experiments 2a-c) it is likely that this lack of advantage is a result of a ceiling effect.

Forced-choice recognition test. In Experiment 2a, none of the participants reported noticing the regularity in the visual search task. Accordingly, performance in the recognition test was at chance ($M = 1.5$, $SD = 1$). One participant was correct on 4 out of 8 trials (chance probability of 0.01). Results were recalculated while excluding this participant. All reported results remained significant. In Experiment 2b, there was no regularity. Participants were thus tested for their memory of the presented images. On average participants remembered 66% of the distractors that were presented in the visual search task. This relatively low performance is in line with the overall fast response in the experiment. In Experiment 2c, 4 participants reported noticing "something" during the visual search task. However, none of them performed above chance in the explicit memory test (chance performance was 0.125). Mean accuracy in the task was 2.4 ($SD = 1.2$). Four other participants were correct on 4 out of 8 trials (probability of 0.01), and one participant was correct of 5 out of 8 trials (probability of 0.001). All results were recalculated while excluding all of these participants. All reported results remained significant.

Visual Working Memory capacity: Mean VWM capacity estimate was as follows: 2.75 ($SD = 0.7$) in Exp. 2a (mixed design), 2.7 ($SD = 0.9$) in Exp. 2b (random mapping alone), and 2.77 ($SD = 0.9$) in Exp. 2c (consistent mapping alone). As in Experiment 1, the only correlation between VWM estimation and performance in the visual search task was when the search was random (Exp. 2c) ($r = -0.5$, $p = .003$).

3.3. Conclusions (Experiments 2a-c)

In Experiments 2a-c participants completed a visual search with images of real objects as stimuli. Overall, the RTs in all three experiments were very fast, suggesting that the visual search task was easier than the one used in Experiment 1. However, the interference from mixing regularity with randomness was observed again: performance in the mixed design search (Experiment 2a) was slower than performance in a completely random visual search (Experiment 2b). This result confirms that the results of Experiment 1 were not specific to the type of regularity or stimuli, and that the relative validity of the regularity is indeed a crucial factor that results in an overall slowdown of performance when regularity is mixed with randomness.

Unlike in Experiment 1, when the regularity was valid on every trial (Experiment 2c) performance was not faster than performance in a random visual search (Experiment 2b). This lack of difference is surprising because given the high validity of the regularity it was expected to drive performance beyond general practice effects. One possibility is that this lack of result stems from differences in the group samples between experiments. As the experiments were administered consecutively we cannot rule out this possibility. However, as there were no age, gender or VWM differences between the groups, it is more likely that we did not observe a difference between completely structured and random searches because performance in the random search was already optimal. Fast RTs are typical to visual search tasks that rely on images of real object (Makovski, 2016), probably because they allow participants to extract information other than regularity or general practice. Although this result is interesting, it is not the focus of the current investigation. The important issue is that in both experiments, decreasing incoming validity by mixing regularity and randomness

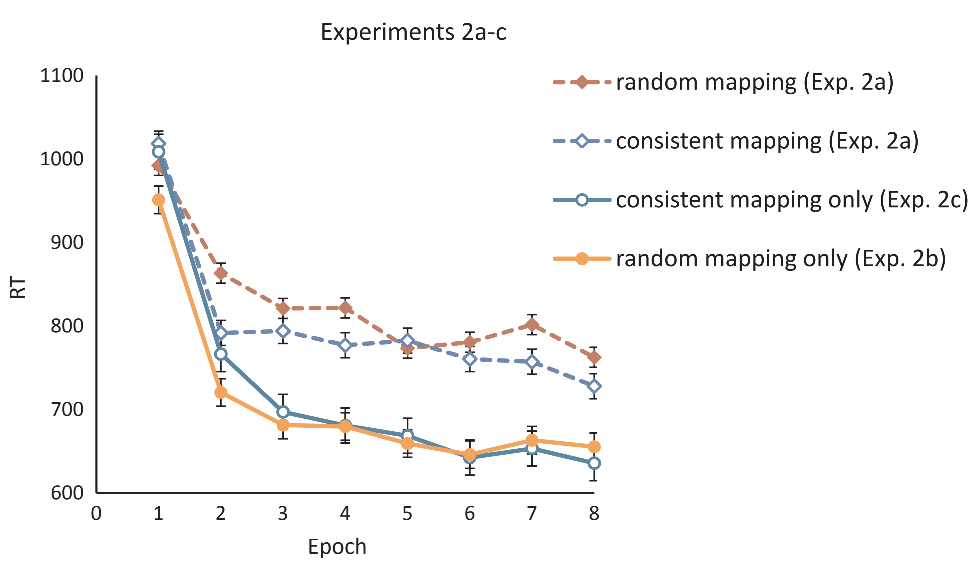

Fig. 4. Results from the visual search task in Experiments 2a (n = 33), 2b (n = 33) and 2c (n = 31). RTs are plotted as a function of epochs (2 blocks per. epoch.) End-of-session performance in Experiment 2a (mixed design) was slower than performance in Experiment 2b (random mapping alone).

resulted in a general slowdown.

4. General discussion

The goal of the current study was to explore the influence of regularity on practice effects from the perspective of predictive processing. Specifically, we identify the predictive value of the regularity as a key factor that modulates the systems' reliance on the accumulating information in the task.

Previous studies suggested that participants can become faster when repeatedly performing a visual search task, even when it does not contain regularity (Clark et al., 2015). To understand how regularity influences practice speedup, we used a visual search task and embedded an implicit regularity that enabled predicting the target's location based on the distractors' locations. Crucially, unlike previous studies, the relative validity of the regularity was systematically manipulated. In Experiment 1, three groups of participants completed a visual search task with T's and L's as stimuli under three distinct reliability situations: highly reliable (consistent mapping group), in which case all spatial layouts of the search displays were kept constant throughout the task, relatively unreliable- a visual search with random and consistent mapping conditions mixed (mixed design group), and random visual search (random group). In Experiments 2a-c we used a similar approach, but relied on a visual search with images of real objects as stimuli and target-distractors identity associations as regularity.

To assess when the presence of regularity drives online performance beyond practice we focuse here on the end-of-session performance (Chun & Jiang, 1998; Kunar et al., 2006, Kunar et al., 2008). This measurement represents the best performance (i.e., fastest RTs) that was achieved in a given session. As in previous studies, when consistent and random conditions were mixed (mixed design group in Experiment 1, Experiment 2a) a contextual cueing effect was observed: participants were faster to find the target in the consistent than in the random condition. However, despite this clear evidence that the regularity was indeed learned, the end-of-session performance in the mixed design task was slower than performance in a completely random visual search task (random groups in Experiment 1, and Experiment 2b).

In general, the results of the present work imply that when regularity is mixed with random trials, the implicit learning of the regularity results in a local facilitating effect (i.e., contextual cueing), and a global detrimental effect. This global effect, which leads to an overall slowdown in performance, has so far been overlooked. Theoretically, in terms of maximizing speed, it would have been better not to look for regularities under mixed conditions. Importantly, the real world conditions are always mixed- beneficial regularities appear among random information and other regularities. Thus, the conclusions of the present study represent a significant and basic aspect of human behavior: our cognitive system is wired to maximize predictability and not speed.

The importance of statistical learning of regularities is well documented. This type of learning enables us to discriminate, categorize, and segment continuous information. As such, it is involved in shaping the basic representations underlying a range of sensory, motor, and cognitive abilities (Frost et al., 2015). For instance, studies in the language domain suggest that statistical learning is a crucial mechanism through which language is acquired both in children (Aslin, Saffran, & Newport, 1998; Saffran, Aslin, & Newport, 1996) and adults (Saffran, 2003). We add to these results, by showing that this mechanism is so important, that it operates even at the expense of ongoing performance.

This conclusion is not predicted by the current contextual cueing literature, but it is in line with studies that test the relationship between Statistical Summary Perception (Ariely, 2001) and statistical learning (Saffran et al., 1996). In Statistical Summary Perception studies observers are typically presented with arrays of objects and asked to report a summary statistic, such as mean size (e.g., Ariely, 2001; Zhao et al., 2011). When, unbeknown to them, the arrays contain statistical regularity, a mutual interference is observed: computing summary statistics interferes with statistical learning, and the presence of regularity interferes with statistical summary perception (Zhao & Yu, 2016; Zhao et al., 2011). At first blush, this interference effect seems different from the results of the present work. Zhao and colleagues did not test practice effects, and their work shows interference to ongoing performance (i.e., mean estimation) when the task requires statistical calculation, but contains an additional regularity. As stated by the authors, this interference may be caused by a competition between two statistical operations. In contrast, we show that just one regularity that is potentially beneficial for the task itself (i.e., search), may cause interference to performance. However, please note that both types of studies show that statistical learning does not depend on the benefit to the task at hand. It would have been better to stop computing regularities between individual objects when the task is to summarize statistics: the estimation was less accurate when the display contained additional statistical information. Likewise, it would have been better to stop looking for regularity when it is mixed with randomness in a visual search task: performance was slower than in a random task. However, in both cases the system continues to compute statistical regularity despite an immediate detrimental effect.

To account for our results, we rely on the prediction-processing framework (Clark, 2013; Lupyan, 2015; Lupyan & Clark, 2015). According to this framework, regularity is information that has a predictive value. When regularity applies to all trials in the task, the predictive value is high. When it applies to half of the trials (e.g., when consistent and random conditions are mixed), the regularity is unreliable and its predictive value is relatively low. We suggest that in this case, the presence of regularity has a detrimental global effect on performance because it reduces reliance on all prior information, thus interfering with general task improvement.

This proposition is supported by previous arguments regarding the ongoing updating of information within a given task. It is well established that there is continuous estimating and re-estimating of *uncertainty* within the system, which results in assigning relative weights to top-down predictions versus current visual inputs (Clark, 2013; Lupyan, 2015; Lupyan & Clark, 2015). Here, the top-down predictions reflect what the system expects given what it already "knows" about the world and about the current context. When the visual input does not match the systems' expectations, as when the regularity is unreliable, a prediction-error occurs. Crucially, these errors effect not just the predictions themselves, but also the extent to which the system relies on these predictions- a mechanism that is referred to as variable precision weighting (Clark, 2013). In contrast, when the visual input matches expectations, as when the regularity is always present, and critically when it is always absent, it applied to all trials in the task, resulting in high reliability conditions.

The above described argument leads to two important conclusions. First, from the predictive-processing perspective, learning not to expect regularity (i.e., random visual search) is in itself a type of regularity. This conclusion is in line with studies showing that participants can improve dramatically in a random visual search task (Sireteanu & Rettenbach, 1995; Clark et al., 2015). Second, it implies that mixing regularity with randomness creates more difficult conditions than a completely random visual search task. To summarize, we suggest that even though random and consistent mapping conditions provide very different circumstances, the weight that is assigned to prior information is expected to be similarly high in both cases, so that the optimization of task parameters is not restricted and the end of the session performance is better than when consistent and random conditions are mixed.

Our results may seem to contradict previous findings from a study that explored the formation of the contextual cueing effect (Jungé, Scholl, & Chun, 2007). This work showed that a contextual cueing effect is not observed if participants are first trained in a random visual search task. It is suggested that the absence of regularity in early stages of training creates a "shutdown" that prevents participants from learning regularities later on (Jungé et al., 2007). This conclusion is supported by studies that show primacy effects in statistical learning when the regularity is changed during the task (Gebhart, Aslin, & Newport, 2009; Yu & Zhao, 2015). However, we argue that this constant reevaluation happens when the reliability of the incoming information is not stable. It is entirely plausible, that in the absence of regularity the system stops reevaluating information. Moreover, this shutdown may be precisely what enables general improvement to reach its full potential.

Although the present study focused on visual search, our results have implications beyond the contextual cueing effect and the particular task. A growing body of work now considers implicit and statistical learning to reflect the same phenomenon that relies largely on similar mechanisms (Perruchet & Pacton, 2006), with some referring to this learning as "implicit statistical learning" (Conway & Christiansen, 2006). We provide the first evidence to suggest that the presence of a single potentially beneficial regularity that is relevant to the ongoing task, has a negative effect on the general optimization of task-set parameters (i.e., practice). If this is indeed the case, practice effects in general, regardless of the specific task, are expected to be highly dependent on the predictive value of regularity. We hope that future studies will continue to refine our understanding of the implications of statistical learning on online performance, focusing on characterizing the conditions in which the presence of regularity may hurt general practice, such that completely random conditions result in better performance than performance in a task with a beneficial regularity.

Acknowledgements

This research was supported by The Israel Science Foundation Grant No. 862/17 awarded to Roy Luria.

References

Allon, A., & Luria, R. (2016). Prepdat-an R package for preparing experimental data for statistical analysis. *Journal of Open Research Software, 4*(1), e43.
Ariely, D. (2001). Seeing sets: Representation by statistical properties. *Psychological Science, 12*(2), 157–162.
Aslin, R. N., Saffran, J. R., & Newport, E. L. (1998). Computation of conditional probability statistics by 8-month-old infants. *Psychological Science, 9*(4), 321–324.
Behrens, T. E., Woolrich, M. W., Walton, M. E., & Rushworth, M. F. (2007). Learning the value of information in an uncertain world. *Nature Neuroscience, 10*(9), 1214–1221.
Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society. Series B (Methodological),* 289–300.
Bertels, J., Franco, A., & Destrebecqz, A. (2012). How implicit is visual statistical learning? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 38*(5), 1425–1431.
Brady, T. F., Konkle, T., Alvarez, G. A., & Oliva, A. (2008). Visual long-term memory has a massive storage capacity for object details. *Proceedings of the National Academy of Sciences of the United States of America, 105*(38), 14325–14329.
Buchner, A., & Wippich, W. (1998). Differences and commonalities between implicit learning and implicit memory. In M. A. Stadler, & P. A. Frensch (Eds.). *Handbook of implicit learning* (pp. 3–47). Thousand Oaks, CA: Sage Publications.
Chun, M. M. (2000). Contextual cueing of visual attention. *Trends in Cognitive Sciences, 4*(5), 170–178.
Chun, M. M., & Jiang, Y. (1998). Contextual cueing: Implicit learning and memory of visual context guides spatial attention. *Cognitive Psychology, 36*(1), 28–71.
Chun, M. M., & Jiang, Y. (1999). Top-down attentional guidance based on implicit learning of visual covariation. *Psychological Science, 10*(4), 360–365.
Chun, M. M., & Jiang, Y. (2003). Implicit, long-term spatial contextual memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29*(2), 224–234.
Clark, A. (2013). Whatever next? Predictive brains, situated agents, and the future of cognitive science. *Behavioral and Brain Sciences, 36*(3), 181–204.
Clark, K., Appelbaum, L. G., van den Berg, B., Mitroff, S. R., & Woldorff, M. G. (2015). Improvement in visual search with practice: Mapping learning-related changes in neurocognitive stages of processing. *The Journal of Neuroscience, 35*(13), 5351–5359.
Cohen, A., Ivry, R. I., & Keele, S. W. (1990). Attention and structure in sequence learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 16*(1), 17–30.
Conway, C. M., & Christiansen, M. H. (2006). Statistical learning within and between modalities: Pitting abstract against stimulus-specific representations. *Psychological Science, 17*(10), 905–912.
Endo, N., & Takeda, Y. (2004). Selective learning of spatial configuration and object identity in visual search. *Attention, Perception, & Psychophysics, 66*(2), 293–302.
Fiser, J., & Aslin, R. N. (2002). Statistical learning of higher-order temporal structure from visual shape sequences. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 28*(3), 458–467.
Frost, R., Armstrong, B. C., Siegelman, N., & Christiansen, M. H. (2015). Domain generality versus modality specificity: The paradox of statistical learning. *Trends in Cognitive Sciences, 19*(3), 117–125.
Gebhart, A. L., Aslin, R. N., & Newport, E. L. (2009). Changing structures in midstream: learning along the statistical garden path. *Cognitive Sciences, 33*(6), 1087–1116.
Goujon, A., Didierjean, A., & Thorpe, S. (2015). Investigating implicit statistical learning mechanisms through contextual cueing. *Trends in Cognitive Sciences, 19*(9), 524–533.
Harris, A. M., & Remington, R. W. (2017). Contextual cueing improves attentional guidance, even when guidance is supposedly optimal. *Journal of Experimental Psychology: Human Perception and Performance, 43*(5), 926–940.
Jungé, J. A., Scholl, B. J., & Chun, M. M. (2007). How is spatial context learning integrated over signal versus noise? A primacy effect in contextual cueing. *Visual Cognition, 15*(1), 1–11.
Kane, M. J., Poole, B. J., Tuholski, S. W., & Engle, R. W. (2006). Working memory capacity and the top-down control of visual search: Exploring the boundaries of "executive attention". *Journal of Experimental Psychology: Learning, Memory, and Cognition, 32*(4), 749–777.
Kim, G., Lewis-Peacock, J. A., Norman, K. A., & Turk-Browne, N. B. (2014). Pruning of memories by context-based prediction error. *Proceedings of the National Academy of Sciences of the United States of America, 111*(24), 8997–9002.
Kunar, M. A., Flusberg, S., Horowitz, T. S., & Wolfe, J. M. (2007). Does contextual cuing guide the deployment of attention? *Journal of Experimental Psychology: Human Perception and Performance, 33*(4), 816–828.
Kunar, M. A., Flusberg, S. J., & Wolfe, J. M. (2006). Contextual cuing by global features. *Attention, Perception, & Psychophysics, 68*(7), 1204–1216.
Kunar, M. A., Flusberg, S. J., & Wolfe, J. M. (2008). Time to guide: Evidence for delayed attentional guidance in contextual cueing. *Visual Cognition, 16*(6), 804–825.
Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature, 390*(6657), 279–281.
Lupyan, G. (2015). Cognitive penetrability of perception in the age of prediction: Predictive systems are penetrable systems. *Review of Philosophy and Psychology, 6*(4), 547–569.
Lupyan, G., & Clark, A. (2015). Words and the world: Predictive coding and the language-perception-cognition interface. *Current Directions in Psychological Science, 24*(4), 279–284.
Luria, R., & Vogel, E. K. (2011). Visual search demands dictate reliance on working memory storage. *The Journal of Neuroscience, 31*(16), 6199–6207.
Makovski, T. (2016). What is the context of contextual cueing? *Psychonomic Bulletin & Review, 23*(6), 1982–1988.
Otsuka, S., & Saiki, J. (2016). Gift from statistical learning: Visual statistical learning enhances memory for sequence elements and impairs memory for items that disrupt regularities. *Cognition, 147*, 113–126.
Pashler, H. (1988). Familiarity and visual change detection. *Perception & Psychophysics, 44*(4), 369–378.
Perruchet, P., & Pacton, S. (2006). Implicit learning and statistical learning: One phenomenon, two approaches. *Trends in Cognitive Sciences, 10*(5), 233–238.
Peterson, M. S., & Kramer, A. F. (2001). Attentional guidance of the eyes by contextual information and abrupt onsets. *Perception & Psychophysics, 63*, 1239–1249.
Pothos, E. M. (2007). Theories of artificial grammar learning. *Psychological Bulletin, 133*(2), 227–244.
Reber, A. S. (1967). Implicit learning of artificial grammars. *Journal of Verbal Learning and Verbal Behavior, 6*(6), 855–863.
Saffran, J. R. (2003). Statistical language learning: Mechanisms and constraints. *Current Directions in Psychological Science, 12*(4), 110–114.
Saffran, J. R., Aslin, R. N., & Newport, E. L. (1996). Statistical learning by 8-month-old infants. *Science,* 1926–1928.
Schankin, A., & Schubö, A. (2009). Cognitive processes facilitated by contextual cueing: Evidence from event-related brain potentials. *Psychophysiology, 46*, 668–679.
Shen, K., McIntosh, A. R., & Ryan, J. D. (2014). A working memory account of refixations in visual search. *Journal of Vision, 14*(14) 11:1-11.
Sireteanu, R., & Rettenbach, R. (1995). Perceptual learning in visual search: Fast, enduring, but non-specific. *Vision Research, 35*(14), 2037–2043.
Sobel, K. V., Gerrie, M. P., Poole, B. J., & Kane, M. J. (2007). Individual differences in working memory capacity and visual search: The roles of top-down and bottom-up processing. *Psychonomic Bulletin & Review, 14*(5), 840–845.
Turk-Browne, N. B., Jungé, J. A., & Scholl, B. J. (2005). The automaticity of visual statistical learning. *Journal of Experimental Psychology: General, 134*(4), 552–564.
Vadillo, M. A., Konstantinidis, E., & Shanks, D. R. (2016). Underpowered samples, false negatives, and unconscious learning. *Psychonomic Bulletin & Review, 23*(1), 87–102.
Wolfe, J. M. (1998). Visual search. In H. Pashler (Ed.). *Attention* (pp. 13–73). University College, London Press.
Yu, R. Q., & Zhao, J. (2015). The persistence of the attentional bias to regularities in a changing environment. *Attention, Perception, & Psychophysics, 77*(7), 2217–2228.
Zhao, J., Ngo, N., McKendrick, R., & Turk-Browne, N. B. (2011). Mutual interference between statistical summary perception and statistical learning. *Psychological Science, 22*(9), 1212–1219.
Zhao, J., & Yu, R. Q. (2016). Statistical regularities reduce perceived numerosity. *Cognition, 146*, 217–222.