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Statistical learning in visual search is easier after experience with noise than overcoming previous learning

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ABSTRACT

This study compared adaptation to novel statistical learning following different environmental changes. Three groups of participants completed training with a visual search task. For the Consistent-first group, targets and distractors appeared in predefined spatial locations. For the Random-first group training contained no regularity and for the Mixed-first group training consisted of both consistent and random conditions. During the test phase, all groups received identical consistent and random conditions. Contrary to previous findings we did not observe statistical learning shutdown following experience with random visual search: a contextual-cueing effect was observed for all groups. However the effect was not stable in the Mixed-first group, suggesting an ongoing adjustment process. We conclude that initiating learning after experience with noise (i.e., random search) is easier than overcoming previous learning (i.e., encountering previously learned layouts). We argue that our cognitive system is sensitive to changes in the visual input and is actively searching for regularity even when it is absent.

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Statistical learning; visual search; contextual cueing

Imagine driving from one state to another. As you cross the border and continue with your journey, you realize that some of the traffic rules you have gotten used to no longer apply. Instead, new rules are now in place and have to be learned quickly and to be followed accurately. It is this tension between relying on previous knowledge and adapting to new circumstances that defines the cognitive system's flexibility and our ability to adapt to new situations. In the present work, we focus on a particular aspect of learning in a changing environment: implicit statistical learning (Saffran, Aslin, & Newport, 1996). Specifically, we examined which conditions provide a greater challenge for the cognitive system when adapting to novel learning: overcoming previous learning or initiating learning after experience in a noisy environment (i.e., without regularity). Picking up regularity after experience in a noisy environment may prove to be difficult if the absence of regularity causes the cognitive system to stop looking for one. Picking up a new regularity that replaces pre-existing rules might be challenging because it requires overcoming the expectations to encounter previously learned information. To the best of our knowledge, the present work is the first to directly compare these different conditions.

Statistical Learning refers to an implicit cognitive process in which repeated patterns, or regularities, are extracted from sensory inputs (Turk-Browne, 2012). Although initially introduced in the field of language acquisition (Saffran et al., 1996), the term has been used since to account for the ability to detect and use regularities in various domains (for a review, see Perruchet & Pacton, 2006). To date, evidence suggests that statistical learning is an overwhelmingly strong mechanism. It occurs incidentally, without intention (Bertels, Franco, & Destrebecqz, 2012) and operates even at the expense of task performance (Vaskevich & Luria, 2018; Zhao, Ngo, McKendrick, & Turk-Browne, 2011). The robust nature of statistical learning mechanisms raised the question of proactive interference: does implicit learning of regularity interfere with subsequent learning. Indeed, results point to a strong primacy effect: the first regularity that is encountered is learned faster and better than subsequent regularities (Gebhart, Aslin, & Newport, 2009; Karuza et al., 2016; Manginelli & Pollmann, 2009; Yu & Zhao, 2015). In the present work, we chose to rely on the visual search paradigm (Wolfe, 1998). This is because assessing the influence of regularity in visual search is done during the task

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itself. As such, unlike in other statistical learning paradigms (Gebhart et al., 2009; Karuza et al., 2016; Yu & Zhao, 2015), it allows not just assessing the overall effect of learning a regularity after changes in the environment, but also the assessment of *when* this new learning begins to influence performance.

Testing the effect of regularity in a visual search task is typically done with the Contextual Cueing paradigm (Chun, 2000; Chun & Jiang, 1998): a consistent condition in which the target and distractors positions are fixed, creating an invariant configuration, is repeated across the experiment and is mixed with a variable or random condition in which the target and distractors appear in novel or unrepeated configurations. Numerous studies have shown that participants are faster to find the target in the consistent mapping condition than in the random condition (for a review, see Goujon, Didierjean, & Thorpe, 2015). With regards to changing the regularity during the search task, two aspects were previously explored: *Relearning* and *New-learning* (Zellin, Conci, von Mühlenen, & Müller, 2013). In Relearning, after the initial target locations are presented repeatedly within invariant contexts, the targets are relocated to new locations while the context (i.e., distractors' locations) remains the same. Most results show that participants are unable to learn the new target-distractors associations (Conci, Sun, & Müller, 2011; Makovski & Jiang, 2010; Manginelli & Pollmann, 2009; for a conflicting result see: Luhmann, 2011), although at least one study found that relearning is possible if enough retraining is available (3 days of training with overall 80 repetitions were used) (Zellin, von Mühlenen, Müller, & Conci, 2014). In New-learning, participants are trained in a visual search task with specific target-context associations (i.e., target-distractors sets), that are replaced at some point by new unrelated sets (thus, changing the positions of both the target and the distractors). Results suggested that New-learning is possible, but that it takes considerable time to develop (Zellin et al., 2013). In situations in which new rules are added but previously learned rules are not removed, New-learning was shown to occur only after breaks or sleep (Jiang, Song, & Rigas, 2005; Mednick, Makovski, Cai, & Jiang, 2009).

The key difference between Relearning and New-learning is in terms of the type of interference from prior knowledge. Relearning reflects proactive inference: the same rules that directed you to the targets' locations become misguiding once these targets are moved. In New-learning the main issue is flexibility: new rules must be detected in an environment from which other rules, that no longer appear, have already been extracted. In this case, the previously encountered rules create an expectation that the incoming information is in accordance with what was learned. Presumably, Relearning is more difficult than New-learning because it requires not only overcoming previous expectations and learning new associations, but also the modification of existing specific knowledge- interference from the old rules must be suppressed. Although both types of changes are interesting, in the present study we focus on the overall flexibility of the cognitive system, and thus test the participants' ability for New-learning in a visual search task.

Flexibility is directly connected to the system's expectations: when participants expect to encounter information according to a given regularity, flexibility is crucial in their ability to overcome these expectations and adjust to a new environment. It is important to note, that not only is the regularity expected, but also the rate of its' appearance (Tseng, Hsu, Tzeng, Hung, & Juan, 2011; Zang, Zinchenko, Jia, Assumpção, & Li, 2018; Zinchenko, Conci, Müller, & Geyer, 2018). At least three studies systematically varied the ratio between consistent and random displays in visual search tasks. All demonstrated that experiencing a higher proportion of consistent information facilitates contextual learning, even when the number of the specific displays is kept constant (Zang et al., 2018; Zinchenko et al., 2018). These results suggest that contextual cueing is influenced by global statistical properties of the task. Crucially, global statistics determines the assumptions about the reliability of the environment, which seem to modulate the size and temporal development of the effect. As such, when considering the effects of New-learning it is also important to take into consideration the overall reliability of the environment before the change occurred.

One particular type of New-learning is picking up regularity after experience with noise. Unlike situations in which the regularity is changed during the visual search task (Jiang et al., 2005; Mednick et al., 2009), here regularity is introduced into a task that previously did not contain one (i.e., random visual search). Jungé, Scholl, and Chun (2007) trained two groups of participants in a visual search task with both consistent and random conditions, sequentially ordered. During the test phase, a contextual cueing effect was observed only for the group that completed the consistent search task first, whereas the group that completed a random visual search first did not show any evidence of learning the regularity. The authors suggested that the absence of regularity in the early stages of training created a shutdown that prevented participants from learning the regularity when it was introduced (Jungé et al., 2007). This conclusion seems to be at odds with at least one study in which a contextual cueing effect was observed after a long task-familiarization period (144 trials) with only random trials (Johnson, Woodman, Braun, & Luck, 2007). One possibility for this discrepancy is that Jungé and colleagues did not observe a contextual cueing effect after experience with a random visual search because the test phase was too short: they used only six presentations of each target-distractors set while Johnson et al. (2007) used more than 500 presentations (a contextual cueing effect was observed already after 12 presentations). From this perspective, it is possible that the results observed by Jungé et al. (2007) reflect the hindering of learning and not a complete shutdown effect.

The above described studies provide examples of contextual cueing examination after different types of experience, such as introducing a new regularity after regularity has been learned (Jiang et al., 2005; Mednick et al., 2009) and introducing regularity after experience with noisy (i.e., random) conditions (Johnson et al., 2007; Jungé et al., 2007). However, it is impossible to compare these studies directly because they rely on very different experimental designs. Not only do they differ in the number of trials, number of sessions, and the specifics of the visual display, they also differ in the type of training used, with either a sequential (Jungé et al., 2007) or mixed (Jiang et al., 2005; Mednick et al., 2009) presentations of random and mixed conditions. Thus, it is currently unclear which conditions provide a greater challenge for the cognitive system: overcoming previously learned regularity, or learning regularity after experience in an environment without any regularity. To provide a test for this issue, in the present study we relied on a single experimental design in which we systematically varied the conditions during the training phase, so that the contextual cueing effects observed during the test phase are comparable both in terms of temporal development and overall size of the effect.

Three groups of participants completed a visual search task. During training, the task contained either a consistent-mapping condition (Consistent-first group), a random-mapping condition (Random-first group), or both conditions mixed (Mixed-first group). During the test phase, all groups performed mixed consistent and random conditions and a contextual cueing effect was assessed. For the Mixed-first and Random-first groups the test phase contained new, never before seen target-distractor layouts. Comparing these two groups enabled us to assess contextual cueing after a change that reflects overcoming noise (Random-first group) and a change that reflects overcoming previous expectations (Mixed-first group). Importantly, all other aspects of the task were identical between the two groups so that any differences that are observed in the development and size of the contextual cueing effect during the test phase should be attributed to the different training conditions in the two groups (i.e., presence or absence of regularity). Crucially, the test phase in the current study was significantly longer than the one used in by Jungé et al. (2007). If the reported shutdown in statistical learning is only temporary, a contextual cueing effect should eventually emerge. To assess flexibility, we identify when the contextual cueing effect emerges during the test phase. If initiating learning after experience with noise is easier than overcoming previous knowledge, a contextual cueing effect should emerge in the Random-first group before the Mixed-first group.

As described above, apart from the Random-first and Mixed-first groups we also ran a Consistent-first group. For this group half of the layouts that appeared during training continued to appear during the test phase, mixed with random trials. Note that for this group the test phase does not reflect New-learning as the consistent layouts were learned during training. However, it enabled us to assess a contextual cueing effect under conditions in which similarly to the other two groups there was a change in the environment, but no change to the regularity itself. The contextual cueing effect that is observed during the test phase of this group reflects continuous learning of regularity after a change in the global statistics of the task and thus the overall reliability of the environment.

Method

The data was aggregated and organized before the statistical analysis using prepdat (Allon & Luria, 2016). All collected data is available through Open Science Framework: https://osf.io/wkg59/

Participants

As in our previous work, we relied on a sample size of 30 participants in every group (Vaskevich & Luria, 2018). Ninety-three students (71 females, mean age 23, SD = 3) 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: Mixed-first group mean age 23.8, 20 females, Consistent-first group mean age 23.6, 25 females, Random-first group mean age 22.7, 24 females ($F < 1$ for all comparisons). Three participants were discarded from the analyses: one that exhibited very low accuracy rates (<3 SD), and two that did not complete the task (see results). All analyses are reported for the remaining ninety participants.

Stimuli and procedure

Stimuli and procedure were identical to the ones administered in our previous work (Vaskevich & Luria, 2018). All participants gave informed consent following the procedures of a protocol approved by the Ethics Committee at Tel Aviv University. Participants then completed three tasks in the following order: visual working memory (VWM) capacity assessment, visual search task and a memory test that assessed explicit knowledge of regularities. 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 that were made up of two lines of equal length and thickness. 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 centre by 0.1° (Figure 1). All items appeared on a black background within an imaginary rectangle (25° × 20°) with a white fixation cross in the middle of the screen (0.4° × 0.4°). Stimuli in the change detection task (VWM estimation) were colourful squares. The colours of the squares were chosen

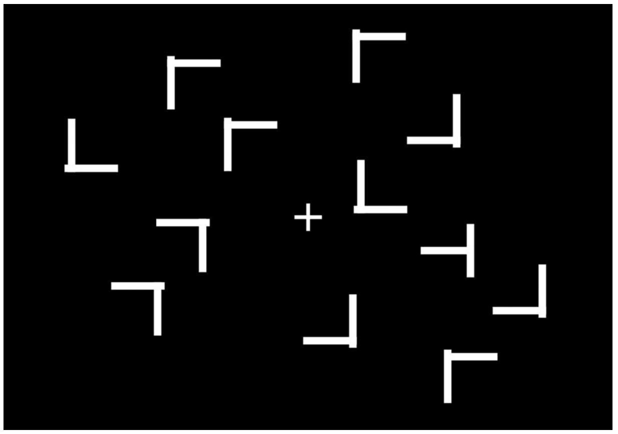

Figure 1. Visual Search task: The target was a T letter rotated either left or right that appeared among rotated L's (distractors). Participants pressed a response key corresponding to the appropriate target as fast as possible. In the consistent mapping condition targets appeared in predefined spatial configurations (i.e., target-distractor sets). In the random mapping condition targets and distractors appeared in random locations.

randomly on each trial from a set of nine colours: red, green, blue, brown, cyan, orange, pink, yellow and black. 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 two squares was 2.1° of visual angle (centre to centre).

Visual Working Memory. The VWM capacity estimation was done with a change detection task (Luria & Vogel, 2011): arrays of either four or eight coloured squares (memory array) appeared in randomly chosen locations for 150 ms, followed by a retention interval of 900 ms after which one coloured square (test probe) appeared at the location of one of the items from the memory array. Participants indicating whether the colour of the test probe was identical or different from the colour of the original item presented in that location (with equal probability for same and different test probes) by pressing one of two keyboard keys in an unspeeded manner. The task was comprised of one intermixed block of 60 trials for each array size (120 trials overall). On changed trials, the changed item was replaced with a colour that did not appear in the memory array. VWM capacity was computed with a standard formula: $K = S(H - F)$, where 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).

Visual search. Participants performed a visual search task looking for a rotated T (target) among heterogeneously rotated L's (distractors). Each trial contained one of two possible targets (left or right rotated T), among eleven distractors (Figure 1). 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. The identity of the target (left or right rotation) was chosen randomly on each trial. The task was divided into two phases: training and test. Each phase contained 24 blocks of 16 trials, so that overall there were 384 trials in both the training and test phases (768 trials overall).

During the training phase, participants completed one or both possible conditions depending on the group. In the Consistent-first group, all trials were from the consistent mapping condition: 16 spatial configurations of targets and distractors were randomly generated for each participant. These layouts (i.e., target-distractor sets) were then kept constant throughout the training phase, so that on each trial a target appeared in a predefined location, surrounded by distractors in the specific spatial layout that was paired with it. Each target-distractors set appeared once in every block. The order of sets was randomized between blocks. In the Random-first group targets and distractors appeared in random locations (within an imaginary rectangle of $25° \times 20°$). In the Mixed-first group consistent and random conditions were mixed: 8 target-distractor sets were randomly generated for each participant. These layouts were then kept constant throughout the training phase and appeared intermixed with random trials: each block contained 8 consistent trials and 8 random trials presented in a random order. The order of target-distractors sets was randomized between blocks. During the test phase all groups completed a visual search task with consistent and random conditions mixed. For the consistent condition in the Mixed-first and Random-first groups 8 new layouts were generated randomly for each participant. For the Consistent-first group 8 of the 16 layouts that were presented during the training phase continued to appear, mixed with random trials. For each participant in the Consistent-first group the 8 layouts that continued to appear during the test phase were chosen randomly from the 16 layouts that appeared during training, regardless of whether they were learned or not. This insured that the contextual cueing observed during the test phase cannot be attributed to the learnability of any specific displays (Zellin, Conci, von Mühlenen, & Müller, 2011).

Note that the use of a random mapping condition is a deviation from the classic contextual cuing experiments that employed a variable mapping condition (Chun & Jiang, 1998). The major difference concerns the positioning of the targets in random displays: in the classic paradigm, target locations are repeated, which allows isolating the specific influence of the distractor context, while in the current study the target locations varied, thus avoiding any consistent information in the random displays. This approach is better suited for the main objective of the present work: comparing New-learning after experience with conditions that contain regularity with New-learning after experience in a noisy environment that does not contain any type of regularity. Additionally, this design should also enable us to assess whether the complete absence of regularity leads to a shutdown of statistical learning.

Explicit memory test. Upon completing the search task participants performed an explicit memory test identical to the test used in our previous study (Vaskevich & Luria, 2018): all spatial layouts were presented without targets (16 layouts for the Consistent-first group, 8 layouts for the Random-first and Mixed-first groups). For each layout, participants indicated where they thought the corresponding target appeared throughout the task by clicking on the screen with the mouse. In order to gain as much insight as possible into any explicit knowledge participants may have, each spatial layout appeared three times.

Results

Visual search

Accuracy was very high for all groups ($M = 0.97$, SD = 0.02 for all groups). One participant in the random-first group exhibited very low accuracy (0.89, > 3SD from the group mean) and was removed from further analyses. Two participants (one from the Mixed-first group and one from the Consistent-first group) did not complete the task. Reaction times (RTs) below 100 ms and above 3000 ms (<6% excluded), error trials and trials immediately following errors were excluded from further analysis. Following previous studies (Chun & Jiang, 1998; Kunar, Flusberg, & Wolfe, 2006; Vaskevich & Luria, 2018), data was grouped into twelve epochs, each consisting of four blocks.

Training phase: During training the three experimental groups completed different visual search conditions. Because the conditions were not factorial (two conditions for the Mixed-first group and one condition for the Consistent-first and Random-first groups), we used two different ANOVA analyses that provided an answer for two different questions: whether there was a contextual cueing effect in the Mixed-first group and whether performance was different between the three experimental groups.

To assess the contextual cueing effect in the Mixed-first group we conducted repeated measures ANOVA with the factors Epoch (1–6) and Condition (consistent mapping/ random mapping). There was a significant main effect of Condition $F(1,29) = 11.7$, $p = .002$, $\eta_p^2 = 0.29$, with significantly faster RTs for the consistent mapping condition ($M = 1338$, SD = 274) than for random mapping condition ($M = 1421$, SD = 263), reflecting a contextual cueing effect. There was also a significant main effect of Epoch, $F(5,29) = 34$, $p < .0001$, $\eta_p^2 = 0.54$, indicating a practice effect. The interaction between Condition and Epoch was not significant ($F < 1$).

Next, in order to assess the difference between the groups during training we conducted a mixed-measures ANOVA with Epoch (1–6) as a within-subjects factor and Group (Consistent-first/ Random-first/ Mixed-first) as a between-subjects factor (Figure 2). For the Mixed-first group RTs were averaged for consistent and random conditions (see also: Vaskevich & Luria, 2018). There was a significant interaction between Group and Epoch $F(10,435) = 2.7$, $p = .003$, $\eta_p^2 = 0.058$. Further analyses revealed that by the end of the training phase the Consistent-first group was significantly faster than the other groups. Consistent with our previous results (Vaskevich & Luria, 2018) performance in the Mixed-first group was not faster than in the Random-first group. The main effect of Epoch was also significant, $F(5,87) = 142.7$, $p < .0001$, $\eta_p^2 = 0.62$, suggesting that performance became faster as time progressed for all groups. The main effect for Group was not significant, $F(2,1) = 1.7$, $p = .2$.

Test phase: During the test phase all groups received both consistent and random conditions mixed. To assess the formation and stability of the contextual cueing effects, we conducted two-way ANOVAs, examining Condition and Epoch for each experimental group. As detailed below, a stable contextual cueing effect was observed only for the Consistent-first and Random-first groups. In contrast, the contextual cueing effect in the Mixed-first group failed to stabilize during the test phase.

For the Mixed-first group there was a main effect of Condition, so that participants were faster in the consistent condition ($M = 1150$, SD = 208) than in the random condition ($M = 1199$, SD = 195), $F(1,29) = 5.48$, $p = .03$, $\eta_p^2 = 0.16$. The main effect of Epoch was also significant, $F(5,145) = 6.4$, $p < .0001$, $\eta_p^2 = 0.18$. The interaction between Condition and Epoch was significant, $F(5,145) = 3.56$, $p = .004$, $\eta_p^2 = 0.16$. Further analyses for the Mixed-first group revealed that the consistent mapping condition became faster than the random mapping condition in Epoch 9, $F(1,29) = 16$, $p = .0004$. However, the effect was not significant in Epoch 10, $F(1,29) = 5$, $p = .034$, and Epoch 11, $F(1,29) = 1.66$, $p = .21$, becoming

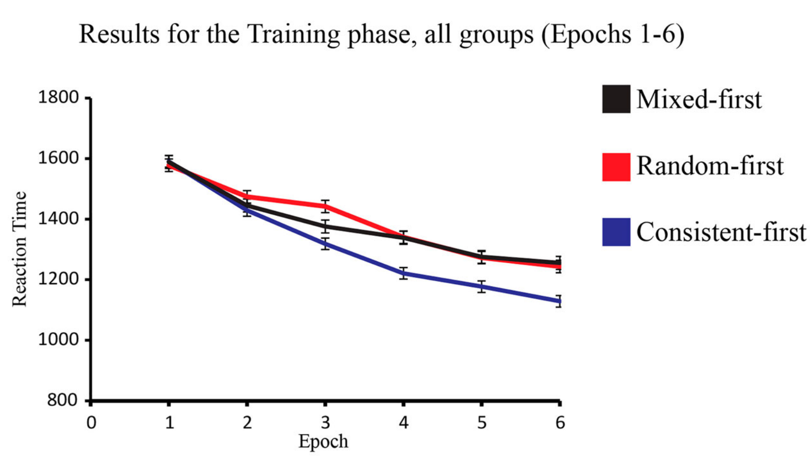

Figure 2. Results from the visual search task for the training phase ($n = 30$ in all groups). RTs are plotted as a function of Epochs (4 blocks per. epoch). By the end of the training phase the Consistent-first group was significantly faster than the other groups. Performance in the Mixed-first group was not faster than in the Random-first group.

significant again only in Epoch 12, $F(1,29) = 10.7$, $p = .003$ (FDR corrected p value was $p = .025$ (Benjamini & Hochberg, 1995)), (Figure 3(a)). Note that the p value for Epoch 10 was considered not significant because it is larger than the corrected p value (.025). These results show that the contextual cueing effect that was observed in the Mixed-first group during the test phase was unstable. Previous studies that identified a time course for a specific effect refer to the first time in which the effect is observed, and remains significant for the duration of the experiment (e.g., Drew, Horowitz, Wolfe, & Vogel, 2012; Luria & Vogel, 2014). Appling the same logic to the present results, we argue that the contextual cueing effect in the Mixed-first group became significant in Epoch 12, at best.

For the Random-first group there was a main effect of Condition, so that participants were faster in the consistent condition ($M = 1118$, SD = 205) than in the random condition ($M = 1186$, SD = 201), $F(1,29) = 13$, $p = .001$, $\eta_p^2 = 0.31$. The main effect of Epoch was also significant, $F(5,145) = 8.75$, $p < .0001$, $\eta_p^2 = 0.23$. The interaction between Condition and Epoch was significant, $F(5,145) = 3.77$, $p = .003$, $\eta_p^2 = 0.11$. Further analyses for the Random-first group revealed that

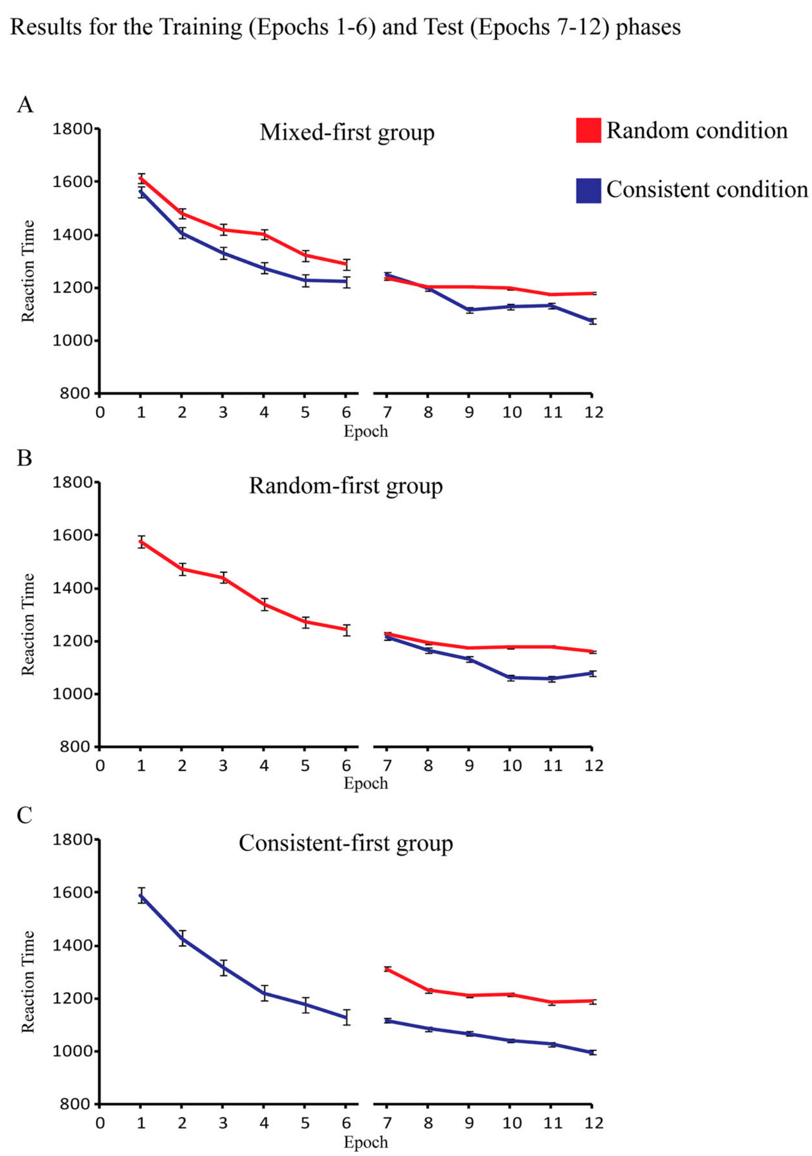

Figure 3. Results from the visual search task for the training (Epochs 1–6) and test (Epochs 7–12) phases ($n = 30$ in all groups). RTs are plotted as a function of Epochs (4 blocks per. epoch). During training, a contextual cueing effect was observed in the Mixed-first group (A). During the test phase a contextual cueing effect emerged and remained significant in epoch 7 for the Consistent-first group (C, Epochs 7–12 sig.) and in Epoch 10 for the Random-first group (B, Epochs 10–12 sig.). For the Mixed-first group the effect emerged in Epoch 9 but became significant again only in Epoch 12 (A).

the consistent mapping condition became faster than the random mapping condition in Epoch 10, and remained significant for the remaining duration of the experiment (all p values smaller than .005, FDR corrected, p value was $p = .025$ (Benjamini & Hochberg, 1995)) (Figure 3(b)). This suggests that unlike the Mixed-first group, the contextual cueing effect in the Random-first group was stable and reliable once it emerged.

For the Consistent-first group there was a main effect of Condition, so that participants were faster in the consistent condition ($M = 1056$, $SD = 188$) than in the random condition ($M = 1224$, $SD = 178$) throughout the test phase, $F(1,29) = 49$, $p < .0001$, $\eta_p^2 = 0.62$. The main effect of Epoch was also significant, $F(5,145) = 97$, $p < .0001$, $\eta_p^2 = 0.24$. The interaction between Condition and Epoch was not significant $F(5,145) = 1$, $p = .42$, (Figure 3(c)). This result is not surprising, as unlike in the other two groups the layouts that appeared during training continued to appear during the test phase. The contextual cueing effect was significant from the beginning of the test phase and is not a case of New-learning. We will return to this result and its implications on our understanding of the role of global statistics in contextual cueing in the Discussion.

To summarize the results so far, during training a contextual cueing effect was observed in the Mixed-first group. This suggests that participants were able to detect and rely on the regularity embedded in the task. By the end of the training phase the Consistent-first group was significantly faster than the other groups. Performance in the Mixed-first group was not faster than performance in the Random-first group even though it contained a beneficial regularity. This pattern of results is a replication of our previous findings (Vaskevich & Luria, 2018). During the test phase a contextual cueing effect was observed for all groups. The main question of the present work was to assess New-learning after training conditions with and without regularity. To do so, we assessed the formation of the contextual cueing effect during the test phase in the Mixed-first and Random-first groups. Our results show that the effect was stable for the Random-first group but not the Mixed-first group, suggesting that overcoming previous expectations is more difficult than initiating learning after experience with a random visual search.

To assess the overall size of the contextual cueing effect during the test phase we collapsed the difference between conditions across the last three Epochs of the test phase (Chun & Jiang, 1998; Kunar et al., 2006) in the Mixed-first and Random-first groups. The Consistent-first group was excluded from this analysis because the contextual cueing effect in the test phase of this group does not reflect New-learning. A one way ANOVA with the factor Group showed there was no significant difference between the sizes of the contextual cueing effects in the Random-first ($M = 107$, $SD = 101$) and Mixed-first groups ($M = 72$, $SD = 135$), $F(1,58) = 1.3$, $p = .26$. This result suggests that although it is easier to initiate and rely on previous information after experience with noise than after performing in a task that contains regularity, the advantage is not permanent. Presumably, given enough time the contextual cueing effect in the Mixed-first group is expected to stabilize, such that the incoming information is relied upon to the same extent as in the Random-first group. Overall, this result illustrates that our cognitive system is extremely flexible, so that we are able to adjust to new circumstances after experience with different types of environments without any long lasting consequences.

Change from training to test. When the training phase contains regularity (Consistent-first and Mixed-first groups) some disruption to performance is expected in the consistent condition. However, the difference in performance between the last epoch of training and the first epoch of test (epochs 6 and 7) in the consistent condition was not significant ($F < 1$) for both Consistent-first and Mixed-first groups. One possibility is that the disruption is short lived, so that by the end of epoch 7 it has already been overcome. To test this possibility, we compared performance in the consistent condition of both Consistent-first and Mixed-first groups between the last block of the training and first block of the test phases (block 24 and 25). In the Consistent-first group the difference was significant, $F(29,1) = 6.3$, $p = .02$ $\eta_p^2 = 0.18$, and in the Mixed-first group it was marginally significant, $F(29,1) = 3.3$, $p = .08$. These result indeed point to a short lived interference effect in the consistent-mapping conditions.

Explicit memory test

In the explicit memory test, each layout was presented three times, without the target. Participants indicated where they thought the target appeared with a mouse click on the screen. For each target, we calculated the distance between the correct location and participant's answer. An answer within a radius of 3° from the centre 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. Four participants in the Random-first group, five in the Mixed-first group and nine in the Consistent-first group matched this criterion for one layout. Four participants matched this criterion for two layouts (2 in the Consistent-first group and one in each of the other two groups). These results are similar to our previous work (Vaskevich & Luria, 2018). All results were recalculated while excluding these participants. All reported results remained significant, except the interaction between Group and Epoch in the training phase $F(10,325) = 1.12$, $p = .34$, so that participants in the Consistent-first group did not reach better performance than in the other two groups during training.

To check whether explicit knowledge had an impact on performance following change, we also looked at the difference between participants with and without explicit knowledge during the test phase. In this assessment we focused only on the Consistent-first and Mixed-first groups because for the Random-first group there was no explicit knowledge before the change (no regularity during training). In the Consistent-first group, participants with ($n = 11$) and without ($n = 19$) explicit knowledge showed similar RTs during training, while during the test phase participants with explicit knowledge were numerically slower in both the consistent (88 ms difference) and random (78 ms) conditions. The same pattern was observed in the Mixed-first group: no differences between participants with ($n = 6$) and without ($n = 24$) explicit knowledge during training, and numerically slower RTs for participants with explicit knowledge following a change (98 ms difference in the consistent condition and 71 ms difference in the random condition). Because only a few participants showed traces of explicit knowledge, we collapsed participants with ($n = 17$) and without ($n = 43$) explicit knowledge across the two experimental groups. The difference between participants with and without explicit knowledge did not reach significance in both the consistent, $F(58,1) = 1$, $p = .32$, and random, $F(58,1) = 2.754$, $p = .1$, conditions. However, as the explicit group contained only 17 participants, it is possible that the differences did not reach significance due to lack of statistical power.

To summarize, explicit knowledge did not seem to play a crucial role in the contextual cueing effects observed in the present work. However, it is possible that explicit knowledge provided participants with an advantage when all trails were consistent (training phase of Consistent-first group). Furthermore, explicit knowledge during training seems to slow down performance when a change is made in the environment. We further address these results in the Discussion. However, it is important to note that dividing participants into those with explicit and implicit knowledge resulted in relatively small subgroups for all comparisons, thus reducing statistical power significantly. As such these results should be treated with caution.

Visual working memory capacity

Mean VWM capacity estimate was as follows: 2.5 (SD = 0.87) in the Mixed-first group, 2.6 (SD = 0.82) in the Random-first group, and 2.65 (SD = 0.88) in the Consistent-first group. There was a significant negative correlation between the VWM estimation and overall RTs during the training phase in the Random-first group ($r = -0.37$, $p = .041$). This result is consistent with previous findings (Luria & Vogel, 2011; Vaskevich & Luria, 2018; but see also: Kane, Poole, Tuholski, & Engle, 2006). Two correlations were observed in the Consistent-first group: a negative correlation between VWM and RTs during training ($r = -0.46$, $p = .013$) and a correlation between the VWM and the size of the contextual cueing effect during the test phase ($r = 0.37$ $p = .049$). To test whether these correlations depended on explicit knowledge we repeated the analyses with participants that had no explicit knowledge of the display (n = 19). Both the correlation between VWM and RTs during training ($r = -0.45$) and the correlation between VWM and contextual cueing during the test phase ($r = 0.4$) remained high but were marginally significant ($p = .053$, $p = .088$ respectively).

Discussion

In this work we examined implicit learning of regularity in a changing environment with two goals in mind. First, we wanted to compare statistical learning of a new, never before seen regularity (New-learning), after different training conditions (with and without regularity). Second, with regards to statistical learning after training with noise (i.e., random conditions) we aimed to test whether the previously reported shutdown (Jungé et al., 2007) is temporary or long-lasting.

Three groups of participants completed training with a visual search task. For the Consistent-first group, all trials during training were consistent: targets and distractors appeared in predefined spatial locations that were kept constant throughout the task. For the Random-first group, there was no regularity during training, and for the Mixed-first group training consisted of both consistent and random conditions, as in the classic contextual cueing paradigm (Chun & Jiang, 1998). During the test phase all groups received consistent and random conditions mixed and a contextual cueing effect was assessed.

A contextual cueing effect was observed for all groups during the test phase. In order to assess the temporal development of the effect we identified the time (i.e., Epoch) in which the effect first became significant and remained significant until the end of the test phase (Drew et al., 2012; Luria & Vogel, 2014). This approach enabled us to assess when it was reasonable to assume that participants are continuously extracting and relying on the regularity. The relevant comparison for evaluating New-learning after different training conditions is between the Random-first and Mixed-first groups. For both groups all aspects of the task were kept constant except the presence or absence of regularity during training. In the Random-first group a reliable difference between the consistent and random conditions was observed in Epoch 10 and was significant for the remaining of the test phase. For the Mixed-first group an effect emerged in Epoch 9, however it proved to be extremely unstable becoming significant again only in the last Epoch of the experiment (Epoch 12).

At first blush, these results may seem to contradict a previous study in which no contextual cueing was observed after experience with a noisy visual search (Jungé et al., 2007). However, there are at least three major differences between this study and the present work that could explain this discrepancy: length of test phase, the amount of changes during training and the type of noise used. First, the length of the test phase in the present study was considerably longer than the one employed by Jungé and colleagues that tested for a contextual cueing effect with six presentations of every target-distractors layout. As the contextual cueing effect in the Random-first group of the present study emerged after 16 presentations of every layout, it is completely in line with this previous result. Another central difference is that in the present work participants experienced only one type of training, while in Jungé et al. (2007) both consistent and noisy conditions appeared during training. Finally, the "noise" conditions used by Jungé et al. (2007) was actually a variable mapping visual search condition, instead of a random condition used in the present design. In a variable mapping condition the positioning of targets in the displays is kept constant, while the distractor sets are varied. From the perspective of the present work a variable mapping condition contains regularity that is not beneficial. It is possible that experience with a non-beneficial regularity causes a shutdown of the implicit learning mechanism, while experience with a random search, without any regularity, does not have the same effect. At the very least our results show that there are conditions in which experience with randomness does not lead to an overall shutdown of statistical learning. We suggest that at least in the present work, the previously reported shutdown is better described as an adjustment period after which the system is able to pick up and rely on regularities from the visual input.

The main motivation of the present work was to test the system's flexibility following different environmental changes. Given the above described pattern of results, we conclude that overcoming previous expectations provides a greater challenge for the cognitive system than initiating learning after experience in a noisy environment: the test phase proved to be sufficient for New-learning (i.e., reliance on new rules) to stabilize in the Random-first group but not in the Mixed-first group. Note that if there is no expectation of shutdown of statistical learning after experience with noise this result is hardly surprising. For both the Mixed-first and Random-first groups transferring from training to test requires an adjustment in expectations: new rules are introduced into the task. However, in the Mixed-first group this adjustment is more difficult because apart from general expectations, there is also *specific* information that has to be overcome: the expectation to encounter previously learned target-distractor layouts.

In general, our results suggest that our cognitive system is quite flexible: even though New-learning began later in the Mixed-first group and was less stable than in the Random-first group, these advantages were not long lasting: when comparing the size of the contextual cueing in the second half of the test phase there was no difference between the two groups. As such, it is worth comparing our results to previous findings that show less flexibility. Mednick et al. (2009) found evidence for New-learning only after sleep or sufficient breaks (see also: Jiang et al., 2005). This result is at odds with the pattern we observed for the Mixed-first group: although the contextual cueing effect was not stable, participants clearly were starting to pick up on the regularity which resulted in a contextual cueing effect in some of the epochs during the test phase. Presumably, the test phase in the Mixed-first group reflects an adjustment and reevaluation period that has not yet come to an end. However, no sleep or break was required for participants to begin this adjustment to new circumstances. One important difference between the two studies is that in the present work the old regularity was removed during the test phase, while Mednick et al. (2009) tested participants for New-learning with the old rules still present. The authors propose that the old regularity creates interference (i.e., blocking) that prevents the acquisition of new rules, and that this interference is reduced by sleep (Mednick et al., 2009; Wixted, 2004). Our results support this suggestion, as removing the old regularity facilitated in the initiation of New-learning even without sleep. Further support can be found in the study conducted by Zellin et al. (2013), who also show a contextual cueing effect during New-learning, when the initial rules have been removed and the test phase is sufficiently long (experiment 2B).

The current study also bares implications on our previous work in which we identified the role of validity in implicit learning (Vaskevich & Luria, 2018). The training phase of the current study was identical in its design to one of our previous experiments and resulted in the same pattern of results. Performance in the Consistent-first group was the fastest by the end of the training phase than performance in the other two groups. However, participants in the Mixed-first group did not reach better performance than participants in the Random-first group even though it contained a potentially beneficial regularity. This result provides additional support for our previous argument that mixing regularity with random trials leads to a global detrimental effect on performance because the regularity becomes relatively unreliable (Vaskevich & Luria, 2018). Crucially, unreliable conditions (i.e., low validity) are expected to reduce reliance on all of the accumulating information in the task. With regards to the present study, it is possible that the low validity of the regularity during training was responsible, at least partly, for the unstable contextual cueing effect observed during test in the Mixed-first group.

The impact of validity is well illustrated by the pattern of results in the Consistent-first group. During training validity was nearly optimal: all targets appeared in predefined locations and in invariant layouts. Not surprisingly, during the test phase a contextual cueing effect was observed as soon as random trials were introduced. However, note that the difference between consistent and random conditions was due to the slow responses in the random condition. Presumably, this interference stems from the surprise in the visual display: targets suddenly began to appear in never before seen locations. In validity terms, these new locations were extremely unexpected. Even though in the present example expectations were very strong, we argue that a similar process happens in every contextual cueing paradigm. The regularity in the consistent mapping condition creates expectations regarding the targets' locations. These expectations serve as a cue that guides attention to the target's location (Chun, 2000). Importantly, expectations are not met on random trials. Instead, each such trial results in a prediction error (Clark, 2013; Vaskevich & Luria, 2018). We have previously suggested that these prediction errors result in a global detrimental effect on performance because they reduce reliance on all previous information (Vaskevich & Luria, 2018). We add to this argument that these prediction errors also result in a more specific interference to performance on random trials that are mixed with regularity: the target is not where it is expected, making the search more difficult. This suggestion implies that the contextual cueing effect itself reflects not just facilitation to search in the consistent mapping condition, but also interference to search in the random mapping condition.

The above-described argument leads us to suggest a new prediction into the field that examines the impact of global statistics on implicit learning in visual search (Tseng et al., 2011; Zang et al., 2018; Zinchenko et al., 2018). It was recently demonstrated that participants are faster in a consistent condition when the ratio between consistent layouts and noise is high (Zinchenko et al., 2018). The accepted interpretation of this result is that global task statistics modulates implicit statistical learning such that higher ratio of presentation facilitates the learning of context. A related interesting question would be how such global statistics affects the noise condition. We predict that under conditions with high rate presentation of consistent displays, noise trials should be slower than when the presentation rate of consistent displays is low. This is because they reflect conditions under which a highly anticipated regularity is not observed, creating a greater interference effect than when regularity is rarely encountered. The experimental design employed by Zinchenko and colleagues does not allow a test for this suggestion (noise trials were collapsed between experiments), therefore it is for future studies to determine whether this prediction is correct.

It is interesting to examine the results of the present work while considering the debate of whether contextual cueing relies on explicit or implicit knowledge. Previous studies showed conflicting results with some suggesting that the effect is implicit (Chun, 2000; Chun & Jiang, 1998) while others arguing that the standard memory tests used are not sufficient to detect explicit knowledge (Schlagbauer, Rausch, Zehetleitner, Müller, & Geyer, 2018; Vadillo, Konstantinidis, & Shanks, 2016). In the present study, we employed a highly sensitive memory test: instead of answering whether a specific layout was seen before (yes or no questions), participants were presented with the layout and asked to place the target within the display. This test enabled us to calculate the distance between the real target location and the location indicated by participants, thus identifying even the slightest evidence for explicit knowledge. In general, despite the high sensitivity of the memory test, our results suggest that the contextual cueing effect does not rely on explicit knowledge: all four contextual cueing effects observed in the present work remained significant when controlling for explicit knowledge. As such, the present study provides strong evidence to support the view that at least when consistent and random conditions are mixed, explicit knowledge is not necessary for contextual cueing to occur. To provide a full summary of our findings we discuss below the effects of explicit knowledge separately during the training and test phases, then consider the role of explicit knowledge specifically with regards to changes in the environment (i.e., from training to test).

During training, the advantage in performance of the Consistent-first group over the other two groups disappeared when participants with explicit knowledge were excluded from the analysis. This pattern is a replication of our previous findings (Vaskevich & Luria, 2018). For the Mixed-first group, the difference between consistent and random conditions (i.e., contextual cueing effect) remained significant when controlling for explicit knowledge. Similarly, during the test phase, the contextual cueing effect remained significant for all groups even when participants with possible traces of explicit knowledge were excluded from the analyses. We next examined the impact of explicit knowledge during the training phase on performance during the test phase within the two groups that could potentially contain explicit knowledge before the change in the environment (Consistent-first and Mixed-first groups). Interestingly, explicit knowledge during the training phase may have slowed participants down after the task changed: both for the Consistent-first and Mixed-first groups there were no differences between participants with and without explicit knowledge during training, while performance was actually numerically slower for participants with explicit knowledge during the test phase (both in the consistent and random conditions, 84 ms difference in the Consistent-first group and 85 ms difference in the Mixed-first group). A possible explanation for this result is that the presence of explicit knowledge made the environmental changes more salient, thus creating an interference to performance. However, note that even though slower performance for participants with explicit knowledge was observed in all epochs for both Consistent-first and Mixed-first groups during the test phase, these differences were not statistically significant. Given the stable pattern of the results, it is likely that this result did not reach significance due to lack of statistical power. In general, it is important to bear in mind, that dividing participants into those with and without possible traces of explicit knowledge created subgroups with a relatively small number of participants (for a detailed account see the Results section). As such, all the findings in the present study that include explicit vs. implicit comparisons should be treated with caution and need to be tested directly before any further interpretation.

Apart from the visual search task, VWM was estimated for all participants in the study. In general, WM was previously shown to play a crucial part in explicit, but not implicit learning (Kaufman et al., 2010; Unsworth & Engle, 2005; but see also: Bo, Jennett, & Seidler, 2011). Specifically in the case of contextual cueing, most studies suggest that if the effect relies on WM, it is on spatial, not visual WM resources (Annac et al., 2013; Manginelli, Langer, Klose, & Pollmann, 2013; Vickery, Sussman, & Jiang, 2010). We add to these findings by showing that there is no correlation between VWM and statistical learning also in tasks that requires flexibility and adjustment: no correlations were observed during the test phase in the groups that involve New-learning. A Correlation between RTs and VWM was found when the search task did not contain regularity (training phase in the Random-first group). This result is consistent with our previous findings (Vaskevich & Luria, 2018). Unlike in our previous work, we observed a correlation in the consistent-first group between VWM and RTs during training and a correlation between the size of contextual cueing and VWM during the test phase. This surprising result cannot be explained by explicit knowledge: when participants with such knowledge were removed from analyses the correlations were still high and marginally significant. However, in light of previous findings, and the fact that we did not observe similar correlations between VWM and the consistent conditions in a previous study (Vaskevich & Luria, 2018), we suggest treating the correlations observed in the Consistent-first group with caution and assessing the issue further in future studies.

To summarize, our results suggest that initiating learning after experience with noise is easier than overcoming previous knowledge. This conclusion leads us to argue that our cognitive system is sensitive to changes in the visual input and is actively searching for regularity even when the present conditions do not contain one. Overall, it illustrates the flexibility of the system, which is undeniably necessary for our ability to function in unstable environments. We hope that future studies continue to examine the extent, and limitations of this flexibility and our ability to learn, adjust, and learn again.

Data Availability: All collected data is available through Open Science Framework: https://osf.io/wkg59/.

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