

Investigating implicit statistical learning mechanisms through contextual cueing

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Since its inception, the contextual cueing (CC) paradigm has generated considerable interest in various fields of cognitive sciences because it constitutes an elegant approach to understanding how statistical learning (SL) mechanisms can detect contextual regularities during a visual search. In this article we review and discuss five aspects of CC: (i) the implicit nature of learning, (ii) the mechanisms involved in CC, (iii) the mediating factors affecting CC, (iv) the generalization of CC phenomena, and (v) the dissociation between implicit and explicit CC phenomena. The findings suggest that implicit SL is an inherent component of ongoing processing which operates through clustering, associative, and reinforcement processes at various levels of sensory-motor processing, and might result from simple spike-timing-dependent plasticity.

Contextual cueing: a statistical learning phenomenon

SL refers to an unconscious cognitive process in which repeated patterns, or regularities, are extracted from sensory inputs [1]. Initially introduced in the field of language acquisition [2], the term SL is now invoked in various domains of psychology to account for the human ability to detect and use statistical regularities present in the environment [3–7]. In this respect, an increasing number of theories and models of cognition and development assume that sophisticated human behaviors result, at least in part, from such elementary learning mechanisms (e.g., [5–7]). By structuring the world and by making it coherent and predictable, SL would play a key role in language acquisition, object recognition, scene identification, attentional guidance, and navigation in complex, dynamic environments.

Different approaches have been developed to study how individuals become sensitive to the structured properties of the environment and how SL mechanisms operate. In this regard, the CC paradigm constitutes an elegant way to understand how learning mechanisms can detect contextual regularities during visual search, allowing an optimization of basic visual processing and/or attentional

deployment in subsequent encounters [8,9]. The general principle of the CC paradigm consists of presenting regularities within search displays that allow target location to be predicted, and to expose participants to these regularities throughout the course of the task.

In the standard version of the paradigm [8], participants are instructed to search for a T-target within a configuration of L-distractors. Half the configurations are systematically repeated across many blocks of trials while the others are presented only once during the task. A benefit on search times, termed CC, is typically observed in the repeated contexts compared to the novel contexts (Figure 1). The dominant interpretation to this benefit is that learning of associations between spatial configurations and target locations guides attention to the target location. Because, as with many other forms of SL, this effect usually occurs without instruction, without intention to learn, and without evidence of conscious memory, CC is thought to result from implicit learning (IL) [10].

Since its inception, the CC phenomenon has generated a great deal of interest in various fields of cognitive sciences and offers new insights for the comprehension of implicit SL mechanisms. In this framework, the goal of this article is to overview the most crucial findings and debates which have emerged over the past decade and to discuss five aspects of CC: (i) the implicit nature of CC in the light of controversies regarding IL, (ii) the mechanisms involved in CC, (iii) the mediating factors affecting CC, (iv) the generalization of CC phenomena, and (v) the question of dissociation between implicit and explicit CC phenomena.

CC and controversies regarding IL

Conscious awareness in CC

IL is commonly defined as an unintentional and automatic adaptation to information present in the world without any clear awareness of what has been learnt [11]. This form of learning is thought to contrast with explicit learning (EL), which refers to the acquisition of skills or knowledge with awareness, and with the ability to explain how the skills or knowledge was acquired. However, though it is well accepted that IL produces tacit knowledge, the degree to which this knowledge is totally inaccessible to conscious awareness remains controversial. Although subjective criteria (e.g., verbal reports) suggest that acquired knowledge

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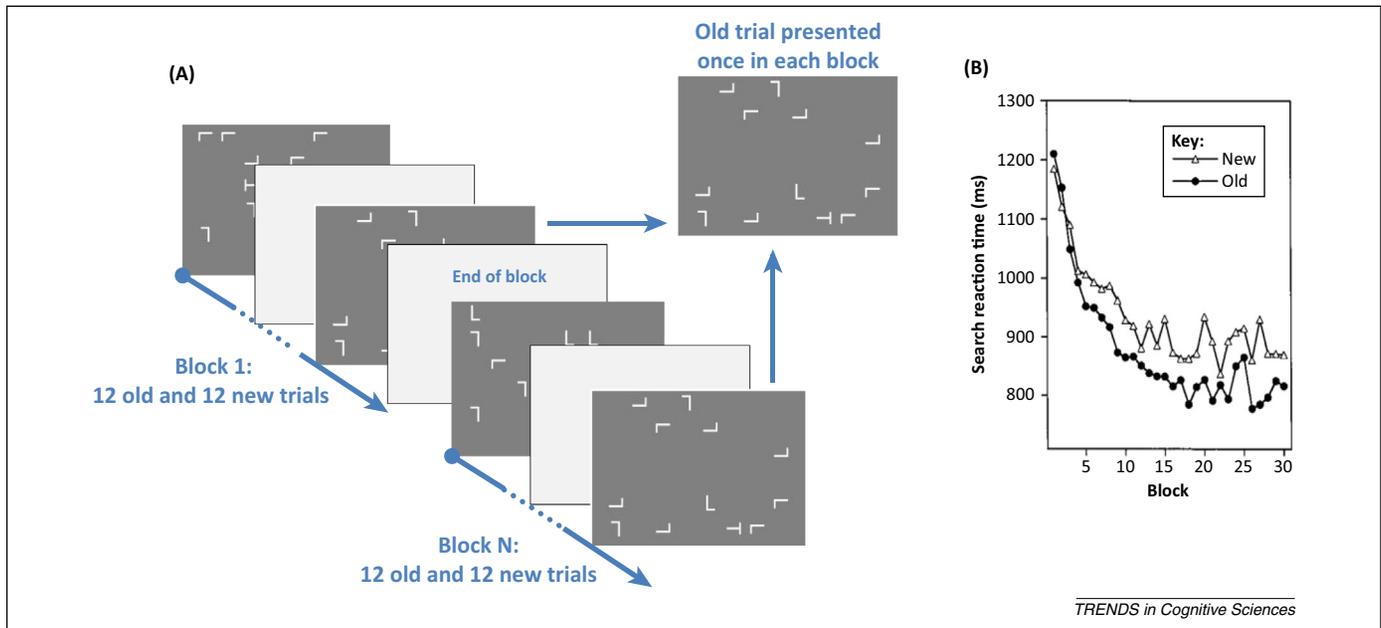


Figure 1. Typical CC task. **(A)** Typical procedure for CC. The task is to search for a rotated T-target among L-distractors. In the typical search task, participants are exposed to a large number of blocks of trials (e.g., 30). Each block usually includes 12 different ‘old configurations’ that are repeated once in each block. The target appears at consistent locations in these repeated configurations. The 12 old configurations are mixed with 12 ‘new’ randomly generated configurations that are presented only once during the entire experiment. **(B)** Typical learning function. Search performance as a function of block is usually faster when targets appear in old configurations than with new configurations. The benefit for old configurations is termed CC. Panel B is adapted from [10]; Copyright ©2003 American Psychological Association and adapted with permission. Implicit CC based on spatial configurations can emerge with both colored and greyscale items [8]. Such effects have been seen in a large number of studies using a wide range of stimuli, including meaningless forms [89] and pseudo-3D displays using pictorial cues to give an impression of apparent depth [102,103]. Spatial CC has also been extended to the haptic modality [104] and to color arrangements; that is, when the spatial layout of colored patches on a matrix predicts the target location [105].

may be unconscious in many incidental learning situations, objective criteria (e.g., familiarity judgments) often lead to inconclusive results [12]. These difficulties in observing learning in the total absence of memory in explicit memory tasks have prompted some authors to question whether any learning can occur in the absence of awareness [13,14]. It is noteworthy that most work in the field of SL relies on subjective judgments of familiarity to index learning, which raises the problem of the status of consciousness in those incidental learning phenomena (Box 1). By contrast, one advantage of the CC paradigm is that knowledge about regularities is indirectly measured through a benefit in search times and, consequently, its evaluation does not rely on either a direct memory task or subjective judgments.

Several arguments suggest that the knowledge underlying CC is inaccessible to awareness. First, at the end of the search task, participants rarely report having noticed that some displays were repeated across the task. More importantly, participants are usually not above chance level in recognition (i.e., at discriminating old configurations from new ones) and target-generation tasks implemented immediately after the search task (e.g., [10]). In a generation task, the target within old contexts is typically substituted by a distractor, and the participants are instructed to guess where the target was located during the search task. Finally, search performance and explicit memory performance in CC are usually not improved by explicit instructions requesting participants to actively encode contextual regularities (e.g., [10]).

Although many studies have reported similar results, some recent studies have questioned the statistical power

of explicit memory tests used in CC studies and suggested that, similarly to many other forms of IL, CC might be ‘contaminated’ by knowledge that leads to some subjective feeling of familiarity during objective memory tasks [15–17]. However, those studies also showed that if some repeated contexts may reach conscious awareness after many presentations, CC performance remains independent of whether the repeated contexts can be judged as familiar or not [15,16]. As a whole, the consensus is that consciousness is not required to account for learning revealed by CC effects [10,16] and that CC provides evidence for the existence of unconscious knowledge.

IL principles and CC

IL is typically characterized according to several principles which fundamentally differ from those supposed to govern EL [18,19]. In this view, IL would emerge slowly over practice but would be very robust over time, resistant regarding numerous psychiatric and neurologic disorders, independent of IQ, insensitive to age effects, and would be driven by primitive mechanisms that are shared with other species. Importantly, IL would be supported by different neural mechanisms than those involved in explicit/declarative memory, which depend on the medial temporal lobe (MTL) and especially on the hippocampus. However, here again research in the field of IL reveals the difficulty to show one situation that firmly obeys all of those principles. What about CC?

As a whole, CC validates numerous IL principles. CC is a robust effect that emerges after about five exposures to repeated configurations and two repetitions when they are associated with reward [20]. This effect persists after

Box 1. Overview of visual SL

The most typical method used to investigate visual SL involves a first phase that exposes participants to structured streams of two or three elements for several minutes (e.g., ABC, DEF, GHI). Immediately afterwards their memory is assessed through a familiarity test in which they must discriminate these triplets or pairs against foils (generated from the same elements but rearranged into new groupings (e.g., AEI, DHL, GKC, JBF)). Using this type of design, SL has been demonstrated with both temporal sequences (e.g., in a continuous stream constructed from triplets, with shapes appearing one at a time, e.g., DEFJKLABC-DEFGHI) and in spatial configurations (e.g., when shapes appear spatially paired in static displays).

Visual SL and IL

SL mechanisms are often claimed to result from ILs. However, because the majority of work relies on subjective judgments of familiarity to assess learning, the status of awareness in SL is unclear. In this respect, recent findings provide interesting insights. The use of both subjective and objective criteria of awareness suggests that participants are, at least in part, aware of their knowledge in visual SL [106,117]. Congruently, the MTL is not only involved but also required for such SL [46]. However, signs of learning can appear in the MTL memory system after a handful of repetitions, even in the absence of awareness according to familiarity measurement criteria [46,118]. Moreover, incidental learning can be as robust as intentional learning [119] SL might thus precede awareness of regular structures, instead of being concomitant with it.

Constraints on visual SL

SL operates spontaneously over the bound features of an object (e.g., shape and color) when those features co-vary during the learning phase, but in a feature-based manner if the covariance between feature dimensions is disrupted during learning [107]. SL can also occur with non-adjacent contingencies (i.e., even when the three items in each triplet do not occur in immediate succession), provided that the visual features of the interfering items are task-irrelevant [3,120]. Learning of temporal sequences can be expressed in static spatial configurations. Reciprocally, learning of statistics defined by spatial configurations can facilitate detection performance in temporal streams [4]. Although such transfer occurs within the visual modality, there is little transfer from the visual to auditory modalities (or vice versa) (e.g., [5,121]).

Mediating factors

Most research suggests that SL is modulated by selective attention (e.g., [3,120]). Nevertheless, if knowledge is assessed through an indirect procedure (e.g., detecting a particular shape within a sequence), there is evidence of learning on task-irrelevant materials [77].

Generalization

Evidence of SL has been observed at the level of scene categories [94], although not as reliably for object categories [122].

delays lasting weeks [21–23] and strongly resists retroactive interference [22,23]. CC is not confined to humans because similar CC effects have been reported in baboons [21] and pigeons [24]. CC has also been shown to be independent of IQ [25], and to remain intact in numerous psychological and neurological diseases, such as schizophrenia [26], dyslexia [27,28], autistic spectrum disorder [29,30], and even Korsakoff's syndrome [31]. CC is nonetheless strongly impaired in Parkinson's [32] and depressed patients [26].

However, contrary to the assumption that IL is stable across individuals, 30% of participants typically fail to show CC [33]. More surprisingly, CC is non-existent in amnesic patients with major damage to MTL structures [34,35]. Given that IL is thought to be independent of the MTL, this result received great interest in the literature [16,36–39] (Box 2). Despite apparent contradictions, this literature leads to the conclusion that the MTL plays a crucial role in implicit CC and that, although not required, the hippocampus might also be engaged even when knowledge remains implicit [16]. In concordance, while some research has shown that CC matures early in childhood [40] and is spared during aging [41], other studies suggest that particular processes engaged in CC might follow a pattern of ontogenetic maturation and age-related decline more similar to those usually associated with explicit memory [21,42–45]. Although seemingly contradictory, diverging results reported in the literature can nonetheless be explained by the variety of mechanisms involved in CC and by the fact that different SL phenomena may be revealed by the CC phenomenon. This view is developed in the next sections.

The CC phenomenon provides furthermore an additional argument to the recent claim that the declarative memory system and even the hippocampus may be involved in the acquisition or expression of knowledge that remains difficult to access consciously (Box 1). This highlights the

necessity to consider memory systems from a processing modes perspective rather than from dissociation based on consciousness [46–49].

Mechanisms for CC

One of the main challenges found in studies using incidental learning procedures is to determine what the participants have indeed learned from the materials and how the acquired knowledge influences behavior. This difficulty is often a source of conflict, especially around the issue of the level of the integration, generalization, and abstraction processes engaged in IL. In the framework of CC, a large body of studies start from the assumption that this effect results from the extraction of repeated global configurations of items (target and distractors) that would serve to guide spatial attention. This supposes associative learning between a global context and the target location, and then a top-down influence of this integrated representation on attentional guidance. By assuming that activation of unconscious knowledge can lead to a top-down modulation of attentional guidance, this hypothesis was unprecedented in the memory literature.

The most convincing argument in favor of this hypothesis came from the observation of a stronger improvement in the search efficiency in the repeated contexts compared to the unrepeated contexts, which was revealed by a stronger reduction of the slope relating response time with set size [8]. However, the difficulty to reproduce a reliable benefit on search slope (e.g., [50–52]) led many authors to reconsider the initial assumption and opened numerous debates regarding the mechanisms that underlie CC. The current crucial issue is whether CC relies indeed on learning of global configurations, or whether this relies on the local context of the target. These two hypotheses lead to very different predictions regarding the level of associative process engaged in CC and the impact of knowledge on behavior.

Box 2. Neural bases of CC

The neural bases of CC support a model in which multiple stages of visual search processing take advantage of contextual repetitions and in which multiple memory systems contribute to produce a CC effect. First, fMRI studies showed that the magnitude of CC was correlated with a deactivation of visual areas, suggesting a perceptual skill-learning effect [38]. Repetition suppression effects were also observed in the inferoparietal lobule, which might reflect perceptually guided spatial orientating or facilitation in response selection. Procedural learning and the involvement of the basal ganglia are supported by findings from neuropsychological studies showing that CC is strongly impaired in Parkinson patients [32].

Perhaps the most unexpected neural correlate concerns the involvement of MTL structures. There is a general consensus that repeating the context triggers rapid reductions in entorhinal/perirhinal cortical activation, regardless of performance in subsequent recognition memory (e.g., [36,37,39], or [38] for a different result with scenes). This rapid reduction in anterior MTL cortex has been ascribed to memory for repeated visuospatial configurations, and more generally to the integration of elements of experience into fused representations, in other words into chunk formation [37]. Even more surprisingly, several studies have reported modifications in the hippocampal activity for repeated contexts [36–38]. The role played by the hippocampus in CC remained nevertheless inconclusive from these studies because the

presence/absence of conscious recollection associated with the modifications was unclear. A recent study seems to provide the missing piece to the puzzle and to reconcile previous apparently contradictory results. Using a procedure designed to assess concurrently both CC and explicit knowledge from single-display analyses, it has been shown that the left hippocampus and parahippocampal gyrus respond differently depending on whether observers did or did not have explicit knowledge of repeated displays [16]. Enhanced activation was observed for ‘explicit displays’, whereas a repetition suppression effect was observed when the repeated contexts remained inaccessible to the recognition. Interestingly, these processing differences emerged long after evidence of CC in RT, suggesting that, if the hippocampus may be involved in CC later in the task, it is not necessary to account for the initial effect. This observation also suggests a functional and gradual reorganization of memory across the repetitions. One hypothesis is that the hippocampus is involved in integrative processing between a context and the target location, a step that would develop after the extraction and formation of configurations in memory.

The implication of the hippocampus in IL constitutes probably the most crucial result for understanding implicit SL mechanisms because it contrasts with the traditional view that this structure is specifically associated with declarative memory and conscious recollection for recognition memory [47,48].

Local hypothesis

Several arguments suggest that learning in the typical task might be reduced to the extraction and formation of a perceptual unit, in other words a chunk [53] that integrates very limited fragmentary parts of the display. First, as in many other IL situations, SL mechanisms involved in CC seem to be bounded to the task-relevant features that are limited to spatially-adjacent contingencies and strongly prone to interference effects (Box 3). More crucially, learning in CC might be reduced to the target and its surrounding distractors. Indeed, repeating the locations of only two or three items in the target quadrant produces as much CC as repeating the entire display, even when participants are trained on global configurations [54,55]. Note, however, that separating the context and target by empty space does not abolish learning, suggesting that chunk formation is more constrained by the perceptual organization of items in the display rather than spatial distance *per se* [54]. Furthermore, although the global context does not need to be repeated, the local benefit is nevertheless dependant both on its relative position in the display and on the availability of a limited amount of peripheral information [56].

How does the local context facilitate the search task? The weak impact of CC on search slope led authors to propose that this may occur at a late stage of searching, by facilitating decisional and/or response-related processes [50,52,57,58]. In agreement, CC has been found to occur when the search efficiency was already maximized, either because the target produced a pop-out single-feature effect [50,59] or because its location was spatially cued [58]. Moreover, event-related potential (ERP) studies indicate a greater positivity 500–600 ms post-stimulus in repeated than in novel displays [58]. Evidence nevertheless suggests an early effect of the repeated contexts during visual search, and more specifically an effect on spatial attention. For example, ERP studies have revealed an enhancement of the N2pc component, presumed to reflect focused attention [60], in repeated compared to unrepeated displays

approximately 200 ms after their onset [57,61]. Repeated contexts might affect spatial attention at two levels.

One possibility is that there is, indeed, attentional guidance, but that this guidance would be limited to within the local context, thus explaining the weak benefit on search slope. However, if CC relies on simple chunk recognition, an alternative hypothesis is that this perceptual unit captures spatial attention in a bottom-up way by using near-peripheral vision. The formation and reinforcement of this perceptual unit across repetitions might be accompanied by an enhancement of its visual saliency [59]. Such a hypothesis in terms of attentional selection might account for a large body of results reported with the standard task, and in particular the enhancement of the N2pc component in repeated contexts, regardless of its involvement in attentional processes, but also the requirement for a limited amount of peripheral information for the expression of CC [56].

By reducing CC to a simple perceptual learning effect, this hypothesis avoids the conclusion that implicit memory controls information processing in a top-down manner. Even more crucially, if a chunk is spontaneously processed as a whole [62], this considerably reduces the associative mechanisms involved in CC and the assumption that the target is integrated within a contextual map. In other words, as with many IL effects, simple perceptual chunking processes and the development of sensitivity to a perceptual structure might be sufficient to lead to a CC effect. One interesting candidate that could account for the formation of perceptual units within noise is spike-timing-dependent plasticity (STDP) [63]. By causing neurons to become sensitive to patterns of incoming spikes that occur repeatedly, this very simple cortex-based learning mechanism could potentially account for SL [64–66] (Box 4).

Global hypothesis

Although numerous studies suggest that CC observed with the standard task mainly relies on the local context of the

Box 3. Constraints and robustness of CC

Flexibility versus hyperspecificity

CC is to some extent flexible. For example, it is preserved despite small perturbations in the position of the items [8] or when the display is combined, spatially shifted, or rescaled [68]. However, CC only tolerates very limited displacements of the items [108] and remains viewpoint-dependent [102], position-specific, and absolute to the configuration [55,109]. In other words, both the local context of the target and its place within the global context are crucial for CC. In addition, although CC supports modification in the surface features of the items, those would be automatically incorporated into learning when they become task-relevant [8,54,81]. Indeed, learning fully transfers across distractor identity changes along dimensions (e.g., color or shape). However, if those dimensions become relevant for finding the target, learning no longer transfers to stimuli defined by an attribute that differs from the target [81]. Furthermore, learning in CC appears to be task-dependant. For example, learning developed during the visual search task was not seen in a change-detection task [110].

Interference effects and robustness of learning

CC is very sensitive to different types of interference. One source of interference is the non-target set of distractors present in the display. For example, the introduction of spatially-irrelevant material between

the target and the predictive repeated context dramatically reduces CC [54,73]. The presence of configurations of distractors that respect Gestalt laws of grouping based on closure, symmetry, size, or color can also produce interfering perceptual effects capable of abolishing CC [111].

A second source of interference is generated by the accumulation of instances in memory. First, analysis of single displays suggests that only a few repeated configurations lead to a CC effect [17]. Consequently, a search task that includes much fewer trials within each block triggers larger CC effects [112]. Congruently, the acquisition of a new set of old displays is strongly impeded by proactive interference, and requires intensive training or a nap to take place [15,23]. Interestingly, sleep has been shown to reduce proactive inference only for the contexts that are not available in recognition task [15].

By contrast, the literature highlights the robustness of learning over time. Indeed, CC does not develop on old contexts that become associated with new target locations [108,113], even after a 24 h break usually thought to reduce proactive interference, or after extensive training with the new associations [114]. Adaptation seems possible but requires 3 days of training with around 80 repetitions with the new target location [23]. In addition, no cost is observed after target relocation to its original location.

target, several findings show that the global context can also play a role. First, studies showed that global configurations are encoded, even independently of the target location [67,68]. More crucially, evidence for guidance by global configurations has been demonstrated under some circumstances [51,69–73]. For example, improvement in search efficiency within repeated contexts was observed when participants received sufficient time to parse or encode the display, either by increasing the difficulty of the task or by giving prior exposure to the spatial layout [51]. Congruently, eye-movement recordings indicate that the probability that the first saccade goes to the target is increased in repeated displays, provided that a preview of the spatial layout precedes the search display [69–72]. The current interpretation is that, when learning is implicit, attentional deployment in familiar displays does not occur immediately but is implemented over time [52] and its time-course remains probabilistic [70,74]. During visual search, several factors and mechanisms (driven top-down

or bottom-up) compete to control attentional guidance, and this might lead to frequent ‘memory failures’ [75]. Giving more time might merely increase the chance that memory-based processing wins the race.

Neural correlates associated with CC provide furthermore strong arguments that CC can rely on integrative processing between a context and the location of the target. The hippocampus might play a crucial role in this integrative processing (Box 2).

In sum, CC reflects various SL mechanisms that occur at different levels of visual search processing. As a result, multiple stages of this processing can take advantage of contextual repetitions to produce a CC effect. As in many other IL situations, a simple perceptual learning hypothesis might be sufficient to account for CC. However, under particular constraints, there is evidence that CC involves associations between discrete elements (e.g., a context and the target location) and that the resulting implicit knowledge can control attentional guidance in a top-down

Box 4. STDP: a biological mechanism for implicit SL

IL is often thought to depend on different neural mechanisms to those involved in explicit/declarative memory. It is nonetheless now well accepted that there is no one alternative general ‘IL system’ in the brain (e.g., the basal ganglia). IL is increasingly viewed as a slow and pervasive plasticity phenomenon throughout the cortex that occurs as a byproduct of processing itself, without supporting the conscious experience of memory retrieval [19].

One mechanism that could be involved in such cortex-based implicit SL phenomena is STDP, a mechanism that varies synaptic strength as a function of the relative timing of spikes in presynaptic and postsynaptic neurons, and which constitutes a form of Hebbian learning. STDP means that incoming synapses that fire immediately before a neuron fires are strengthened, whereas inputs that fire afterwards are weakened [63]. A surprising consequence of such rules is that they naturally lead neurons to become sensitive to patterns of incoming spikes that occur repeatedly, simply because those features occur most frequently [64].

Simulations with large numbers of inputs have demonstrated that a single neuron equipped with STDP will learn to become sensitive to a repeating pattern lasting a few tens of milliseconds embedded within

background noise, even with only a few tens of repetitions [115]. Importantly, such learning is completely unsupervised – there is no need for any instructions about what should be learned. Other studies have shown that, when multiple neurons are listening to the same set of inputs, and there are inhibitory connections between them that prevent them all firing together, they form a competitive learning mechanism in which each neuron learns to respond selectively to different components of input patterns [116]. It has recently been demonstrated that this type of mechanism allows neurons to become sensitive to patterns of spikes produced by real-world stimuli including, for example, cars going by at specific locations within the visual field [66].

Such a mechanism fits well with the fundamental principles of implicit SL (i.e., slow emergence over practice, robustness over time, relative specificity, local preference, rigidity, sensitivity to various types of interfering noise during learning, and strong robustness to proactive interference). Although much remains to be done to bolster this type of model, it nevertheless seems that the basic ingredients are there to understand how the statistics of input arrays can become encoded in a neural network.

manner. Those two levels of learning could help to account for the wide range of divergent results reported in the literature (e.g., age-effects, hippocampus involvement) because different SL phenomena are captured through the single CC phenomenon. The question is then to determine what factors will constrain the types of regularities that will be extracted and used during the search task.

Mediating factors in CC

As highlighted in [Box 3](#), different types of interference influence strongly both the formation/consolidation of perceptual units in memory and associative learning. The spatial and featural organization of the items in the displays can also be crucial. For example, CC is boosted when grouping processes of the items are enhanced, which probably favors extraction of global configurations [76]. Another factor likely to be determinant is attention. Indeed, although both IL and SL phenomena can occur with minimal attentional resources, learning effects are usually weaker than when attention is fully available [1,6,12,77]. CC appears also reduced under high working-memory load provided that a dual-task condition requires significant spatial and concurrent spatial working-memory resources [78,79]. In addition, CC depends on the repeated contexts being attended [80]. Finally, it seems that surface features are automatically integrated into the context representations when they become task-relevant and, therefore, when attention is oriented toward those dimensions [81] ([Box 3](#)).

In concordance with chunking models, attention might play a crucial role in the formation of the perceptual unit: perceptual primitives would only be grouped together when they are simultaneously held in spatial attentional window, which is constrained by working memory limitations [82,83]. Similarly, Brady and Chun [55] proposed that observers would encode only one ‘snapshot’ of the local context surrounding the target in CC because attention is spatially focused around the target when it is detected. The strength of the learning for a given distractor will therefore depend on how far from the center of the spotlight it is located.

This hypothesis presumes that goal/task-directed attentional bias of processing may strongly drive how SL mechanisms are deployed on the materials, even while knowledge remains implicit [84]. In this respect, any minimal modifications in the materials, the procedure, or the instructions given to the participants might fundamentally modify what features of contexts are extracted, how they are integrated, and/or how the context influences the search performance. For example, a typical serial search task probably leads participants to scrutinize the display items one by one, inducing fragmented instead of global representations of the configurations [33]. By contrast, a method that favors processing the global patterns (e.g., previewing the layout) might not only allow encoding and/or retrieving the configurations as a whole but also allow associative learning to take place. As a result, the exposure duration to the displays (usually longer in fMRI studies), the size of the display, the distance to the monitor, the visual angle, and the color of the items are all characteristics that can influence the width of the spatial window of

attention, and consequentially whether the context will be encoded at a local or global level. For example, it has been shown that CC within visually-complex images was affected by the proximity with which the hands were held to the stimuli, suggesting a bias toward detail-oriented processing near the hands [85].

The CC studies revealed nevertheless an interesting effect. Manipulation of attended and ignored sets of distractors during the learning and transfer phases suggests that learning also affects the ignored set of distractors [80,86]. Congruently, though CC is hampered by secondary spatial working-memory tasks, learning develops immediately when those dual tasks are removed [87]. Attention, in terms of selection process as well as in terms of central cognitive resource, might not be required for learning itself but for the expression of the resulting knowledge on behavior.

Generalization of CC

Even though a vast majority of research has dealt with spatial CC, implicit CC has also been extended to other types of statistical relationships, providing additional support that implicit SL cannot be reduced to the formation of perceptual units. For example, implicit CC effects have been shown within ‘arbitrary’ simple arrays when dynamic environments composed of items were moving along predictable trajectories [88] or when the identity or the shape of contextual elements predicted the shape, identity, or location of the target [88–90]. Sequentially structured event durations, event identities, and spatiotemporal event sequences can also guide attention to a point in time as well as to the identity and location of the target event [91]. Implicit CC can furthermore be based on semantic properties of the context provided that the task enhances semantic processing of the materials [86,90,92]. This suggests that CC can also rely on generalization across different stimuli independently of their visual features, and demonstrates how prior knowledge in long-term memory can be integrated into new implicit SL [93,94]. Similar results have been reported with a visual SL procedure ([Box 1](#)).

Nevertheless, to our knowledge, there is no evidence for implicit CC when predictive relationships are perturbed by task-relevant interfering distractors or by a long delay. Integration processes seem to be confined to conditional relations between spatially- and temporally-adjacent elements or events. To be bound together, elements or events of experience might have to co-occur within a short temporal window.

CC has furthermore been shown when repeated real-world scenes [95,96] or meaningless but visually-complex images predicted the target location [97]. However, those effects were strongly associated with awareness of regularities. By revealing both implicit and explicit effects depending of the materials, the CC paradigm offers a promising method to address the question of dissociation between IL and EL.

Dissociation between implicit and explicit CC phenomena

It is often assumed that IL and EL phenomena are subserved by independent processing and memory systems

that are governed by different principles of learning. However, the difficulty to show one learning situation that firmly obeys all of those principles introduces the problem of an operational definition of IL and raises the issue of a clear functional dissociation between implicit and ‘explicit/declarative’ processing and memory in finalized cognitive activities [12,19].

In support for functional dissociation, the differences between CC effects observed when knowledge is associated with conscious awareness compared to when it remains implicit are striking. This review shows that, as a whole, spatial CC validates numerous principles of IL – that is, slow emergence over practice, robustness in the face of time and numerous psychological/neurological diseases, commonality, IQ independency, relative specificity, local preference, rigidity, sensitivity to various types of interfering noise during learning, and strong robustness regarding proactive interference. Furthermore, although IL may exert a top-down control on attentional guidance, its influence on behavior remains fragile, unstable, and probabilistic.

By contrast, when CC is associated with conscious awareness of regularities, for example in visually-complex images [95,97], benefits emerge more rapidly and they are much stronger and more stable across the task [95]. CC relies heavily on global pattern analysis [98], supports important transfer effects and feature manipulations in the scenes (e.g., color-scheme modifications, mirror inversions) [99], is clearly due to a facilitation in attentional guidance [97,100], and precludes item-based CC if both the background and array-based context predict the target location [101]. As such, when regularities are accessible to consciousness, the impact on search efficiency is considerably enhanced.

However, the CC literature also highlights the difficulty to isolate ‘pure’ memory processes. First, CC within arbitrary displays and CC within real-world scenes involve common neural correlates. Both are associated with deactivation of visual cortical areas, the inferoparietal lobule, and the anterior MTL cortex. The hippocampus might also be involved in some cases of implicit CC (Box 2). Together with other findings on implicit SL, this supports recent theories based on memory modes rather than on consciousness, theories according to which the hippocampus would be responsible for integrating information across multiple domains and forming relational, configural, and contextual representations, regardless of the implicit or explicit nature of the resulting knowledge [47,49]. Nonetheless, evidence from CC suggests that flexible organization of different elements of experience according to their interrelations is more often associated with some type of conscious recollection and with an enhancing of hippocampal activity [38]. By contrast, unconscious CC phenomena remain associated with repetition suppression effects [16].

Furthermore, even though knowledge that underlies CC in the typical task is mostly unconscious, ‘contamination’ by explicit knowledge has also been demonstrated [16,17]. Conversely, even though statistical contingencies present in real-world scenes are fully accessible to conscious awareness after extensive training, CC has been shown to first take place at an unconscious level [96]. It is

Box 5. Outstanding questions

- How does pre-existing knowledge or prior experience in memory bias attention during chunking and influence SL?
- What are the relationships between awareness and complex binding operations? How do memories that integrate multiple dimensions of experience evolve over time and consolidate in long-term memory?
- How do different memory systems interact in SL? How might a redescription of explicit and implicit knowledge operate over time and during consolidation?
- To what extent can STDP-based mechanisms account for SL phenomena?
- Is attention required for SL or for its expression?
- Is SL confined to adjacent spatiotemporal contingencies?
- How does sleep affect SL? Does it reduce the interfering effects generated by the accumulation of instances in memory or does it lead to fundamental restructuring of memories within neural networks?

unlikely that the participants intentionally searched for regularities. The quality of their representations regarding the images nevertheless allowed them to recollect consciously those images, and this probably facilitated SL to take place. In subsequent exposure to a similar situation, conscious recollection also allows the individual to exert intentional control and flexibility on her/his behavior, which avoids the frequent ‘memory failures’ that occur when knowledge remains inaccessible to awareness [38]. No intentional cognitive control would be involved; consciousness would emerge spontaneously as the consequence of stable, coherent, and integrated representations. The emergence of regularities to awareness in unsupervised learning situations constitutes a terminological problem to classify this type of learning as explicit or implicit.

Broadly considered, SL phenomena that occur within complex stimuli cannot be considered using a clear dichotomy between explicit and implicit memory systems that would operate in isolation from each other and from the unfolding processing. These phenomena result in large part from interactions between different memory systems that depend on external, slow, pervasive, and cortex-based mechanisms of learning, and on transitory associative representations formed and maintained in the MTL memory system. Several outstanding questions are listed in Box 5.

Concluding remarks

The CC phenomena provide an elegant demonstration that, during visual search, observers develop incidental sensitivity to various types of statistical redundancies present in the environment, and that the resulting knowledge can remain inaccessible to conscious awareness. In concordance with other incidental and unsupervised learning situations, CC operates through clustering, associative, and reinforcement processes at various integrative levels of visual processing, and these contribute to facilitating diverse aspects of visual search, including object segmentation/identification, response selection, or attentional guidance.

At a low level of visual processing, such mechanisms can account for the formation of perceptual units within noise through clustering processes. At a higher level, implicit SL operates through associative mechanisms that bind

together discrete elements or events of experience. The strong constraints in CC are consistent with perceptual chunking, which could involve simple STDP-like mechanisms. Nevertheless, top-down influences of repeated contexts on attention guidance, as well as generalization of implicit CC, show that implicit SL can involve more complex associative processes and, in particular, associative memory between perceptual, semantic, and response information. Similarly to other forms of implicit SL, the MTL is not only involved but is required for implicit CC phenomena. The hippocampus can also be engaged, and especially in complex binding processes. This finding opens new perspective on the functional dissociation between memory systems.

The CC phenomena highlight the ubiquity of SL as an intrinsic component of the ongoing processing instead of an additional mechanism operating in parallel. As a result, such mechanisms do not operate in isolation from integrative processing that involves interaction between different 'implicit' and 'explicit/declarative' memory systems. An important avenue for further research will be to determine how these different systems interact in unsupervised learning situations and how a redescription of explicit and implicit knowledge operates over time and during consolidation processing in memory.

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References

- Turk-Browne, N.B. (2012) Statistical learning and its consequences. In *The Influence of Attention, Learning, and Motivation on Visual Search* (Dodd, M.D. and Flowers, J.H., eds), pp. 117–146, Springer
- Saffran, J.R. et al. (1996) Statistical learning by 8-month-old infants. *Science* 274, 1926–1928
- Turk-Browne, N.B. et al. (2005) The automaticity of visual statistical learning. *J. Exp. Psychol. Gen.* 134, 552–564
- Turk-Browne, N.B. and Scholl, B.J. (2009) Flexible visual statistical learning: transfer across space and time. *J. Exp. Psychol. Hum. Percept. Perform.* 35, 195–202
- Frost, R. et al. (2015) Domain generality versus modality specificity: the paradox of statistical learning. *Trends Cogn. Sci.* 19, 117–125
- Thiessen, E.D. et al. (2013) The extraction and integration framework: a two-process account of statistical learning. *Psychol. Bull.* 139, 792–814
- Gopnik, A. and Wellman, H.M. (2012) Reconstructing constructivism: causal models, Bayesian learning mechanisms, and the theory theory. *Psychol. Bull.* 138, 1085–1108
- Chun, M.M. and Jiang, Y. (1998) Contextual cueing: implicit learning and memory of visual context guides spatial attention. *Cogn. Psychol.* 36, 28–71
- Chun, M. (2000) Contextual cueing of visual attention. *Trends Cogn. Sci.* 4, 170–178
- Chun, M.M. and Jiang, Y. (2003) Implicit, long-term spatial contextual memory. *J. Exp. Psychol. Learn. Mem. Cogn.* 29, 224–234
- Reber, A.S. (1967) Implicit learning of artificial grammars. *J. Verbal Learn. Verbal Behav.* 6, 855–863
- Cleeremans, a et al. (1998) Implicit learning: news from the front. *Trends Cogn. Sci.* 2, 406–416
- Shanks, D.R. and St John, M.F. (1994) Characteristics of dissociable human learning systems. *Behav. Brain Sci.* 17, 367–395
- Vinter, A. and Perruchet, P. (1994) Is there an implicit level of representation? *Behav. Brain Sci.* 17, 730–731
- Geyer, T. et al. (2013) Sleep-effects on implicit and explicit memory in repeated visual search. *PLoS ONE* 8, e69953
- Geyer, T. et al. (2012) Medial temporal lobe-dependent repetition suppression and enhancement due to implicit vs. explicit processing of individual repeated search displays. *Front. Hum. Neurosci.* 6, 272
- Smyth, A.C. and Shanks, D.R. (2008) Awareness in contextual cuing with extended and concurrent explicit tests. *Mem. Cognit.* 36, 403–415
- Reber, A.S. (1992) The cognitive unconscious: an evolutionary perspective. *Conscious. Cogn.* 1, 93–133
- Reber, P.J. (2013) The neural basis of implicit learning and memory: A review of neuropsychological and neuroimaging research. *Neuropsychologia* 51, 2026–2042
- Tseng, Y.-C. and Lleras, A. (2013) Rewarding context accelerates implicit guidance in visual search. *Atten. Percept. Psychophys.* 75, 287–298
- Goujon, A. and Fagot, J. (2013) Learning of spatial statistics in nonhuman primates: contextual cueing in baboons (*Papio papio*). *Behav. Brain Res.* 247, 101–109
- Jiang, Y. et al. (2005) High-capacity spatial contextual memory. *Psychon. Bull. Rev.* 12, 524–529
- Zellin, M. et al. (2014) Long-term adaptation to change in implicit contextual learning. *Psychon. Bull. Rev.* 21, 1073–1079
- Wasserman, E.A. et al. (2014) Pigeons exhibit contextual cueing to both simple and complex backgrounds. *Behav. Processes* 104, 44–52
- Merrill, E.C. et al. (2014) The acquisition of contextual cueing effects by persons with and without intellectual disability. *Res. Dev. Disabil.* 35, 2341–2351
- Lamy, D. et al. (2008) Implicit memory for spatial context in depression and schizophrenia. *J. Abnorm. Psychol.* 117, 954–9561
- Howard, J.H. et al. (2006) Dyslexics are impaired on implicit higher-order sequence learning, but not on implicit spatial context learning. *Neuropsychologia* 44, 1131–1144
- Jiménez-Fernández, G. et al. (2011) Dyslexic children show deficits in implicit sequence learning, but not in explicit sequence learning or contextual cueing. *Ann. Dyslexia* 61, 85–110
- Barnes, K.A. et al. (2008) Intact implicit learning of spatial context and temporal sequences in childhood autism spectrum disorder. *Neuropsychology* 22, 563–570
- Kourkoulou, A. et al. (2012) Implicit learning of local context in autism spectrum disorder. *J. Autism Dev. Disord.* 42, 244–256
- Oldman, E. et al. (2011) Intact memory for implicit contextual information in Korsakoff's amnesia. *Neuropsychologia* 49, 2848–2855
- Van Asselen, M. et al. (2009) The role of the basal ganglia in implicit contextual learning: a study of Parkinson's disease. *Neuropsychologia* 47, 1269–1273
- Lleras, A. and Von Mühlenen, A. (2004) Spatial context and top-down strategies in visual search. *Spat. Vis.* 17, 465–482
- Chun, M.M. and Phelps, E.A. (1999) Memory deficits for implicit contextual information in amnesic subjects with hippocampal damage. *Nat. Neurosci.* 2, 844–847
- Manns, J.R. and Squire, L.R. (2001) Perceptual learning, awareness, and the hippocampus. *Hippocampus* 11, 776–782
- Greene, A.J. et al. (2007) Hippocampal differentiation without recognition: an fMRI analysis of the contextual cueing task. *Learn. Mem.* 14, 548–553
- Preston, A.R. and Gabrieli, J.D.E. (2008) Dissociation between explicit memory and configural memory in the human medial temporal lobe. *Cereb. Cortex* 18, 2192–2207
- Westerberg, C.E. et al. (2011) Neural correlates of contextual cueing are modulated by explicit learning. *Neuropsychologia* 49, 3439–3447
- Manelis, A. and Reder, L.M. (2012) Procedural learning and associative memory mechanisms contribute to contextual cueing: evidence from fMRI and eye-tracking. *Learn. Mem.* 19, 527–534
- Dixon, M.L. et al. (2010) Evidence for intact memory-guided attention in school-aged children. *Dev. Sci.* 13, 161–169
- Howard, J.H., Jr et al. (2004) Implicit spatial contextual learning in healthy aging. *Neuropsychology* 18, 124
- Couperus, J.W. et al. (2011) Visual search and contextual cueing: differential effects in 10-year-old children and adults. *Atten. Percept. Psychophys.* 73, 334–348
- Vaidya, C.J. et al. (2007) Developmental differences in implicit learning of spatial context. *Neuropsychology* 21, 497–506

- 44 Smyth, A.C. and Shanks, D.R. (2011) Aging and implicit learning: explorations in contextual cuing. *Psychol. Aging* 26, 127–132
- 45 Darby, K.P. *et al.* (2014) The role of search speed in the contextual cuing of children's attention. *Cogn. Dev.* 29, 17–29
- 46 Schapiro, A.C. *et al.* (2014) The necessity of the medial temporal lobe for statistical learning. *J. Cogn. Neurosci.* 26, 1736–1747
- 47 Shohamy, D. and Turk-Browne, N.B. (2013) Mechanisms for widespread hippocampal involvement in cognition. *J. Exp. Psychol. Gen.* 142, 1159–1170
- 48 Henke, K. *et al.* (2013) Integrating events across levels of consciousness. *Front. Behav. Neurosci.* 7, 68
- 49 Henke, K. (2010) A model for memory systems based on processing modes rather than consciousness. *Nat. Rev. Neurosci.* 11, 523–532
- 50 Kunar, M.A. *et al.* (2007) Does contextual cuing guide the deployment of attention? *J. Exp. Psychol. Hum. Percept. Perform.* 33, 816–828
- 51 Kunar, M.A. *et al.* (2006) Contextual cuing by global features. *Percept. Psychophys.* 68, 1204–1216
- 52 Kunar, M.A. *et al.* (2008) Time to guide: evidence for delayed attentional guidance in contextual cuing. *Vis. Cogn.* 16, 804–825
- 53 Chase, W.G. and Simon, H.A. (1973) Perception in chess. *Cogn. Psychol.* 4, 55–81
- 54 Olson, I.R. and Chun, M.M. (2002) Perceptual constraints on implicit learning of spatial context. *Vis. Cogn.* 9, 273–302
- 55 Brady, T.F. and Chun, M.M. (2007) Spatial constraints on learning in visual search: modeling contextual cuing. *J. Exp. Psychol. Hum. Percept. Perform.* 33, 798–815
- 56 Zang, X. *et al.* (2015) Invariant spatial context is learned but not retrieved in gaze-contingent tunnel-view search. *J. Exp. Psychol. Learn. Mem. Cogn.* 41, 807
- 57 Schankin, A. *et al.* (2011) Is contextual cuing more than the guidance of visual-spatial attention? *Biol. Psychol.* 87, 58–65
- 58 Schankin, A. and Schubö, A. (2010) Contextual cuing effects despite spatially cued target locations. *Psychophysiology* 47, 717–727
- 59 Geyer, T. *et al.* (2010) Contextual cuing of pop-out visual search: when context guides the deployment of attention. *J. Vis.* 10, 20
- 60 Luck, S.J. and Hillyard, S.A. (1994) Spatial filtering during visual search: evidence from human electrophysiology. *J. Exp. Psychol. Hum. Percept. Perform.* 20, 1000
- 61 Schankin, A. and Schubö, A. (2009) Cognitive processes facilitated by contextual cuing: evidence from event-related brain potentials. *Psychophysiology* 46, 668–679
- 62 Ahissar, M. and Hochstein, S. (2004) The reverse hierarchy theory of visual perceptual learning. *Trends Cogn. Sci.* 8, 457–464
- 63 Markram, H. *et al.* (2012) Spike-timing-dependent plasticity: a comprehensive overview. *Front. Synaptic Neurosci.* 4, 2
- 64 Guyonneau, R. *et al.* (2005) Neurons tune to the earliest spikes through STDP. *Neural Comput.* 17, 859–879
- 65 Agus, T.R. *et al.* (2010) Rapid formation of robust auditory memories: insights from noise. *Neuron* 66, 610–618
- 66 Bichler, O. *et al.* (2012) Extraction of temporally correlated features from dynamic vision sensors with spike-timing-dependent plasticity. *Neural Netw.* 32, 339–348
- 67 Beesley, T. *et al.* (2015) Pre-exposure of repeated search configurations facilitates subsequent contextual cuing of visual search. *J. Exp. Psychol. Learn. Mem. Cogn.* 41, 348–362
- 68 Jiang, Y. and Wagner, L.C. (2004) What is learned in spatial contextual cuing – configuration or individual locations? *Percept. Psychophys.* 66, 454–463
- 69 Pollmann, S. and Manginelli, A.A. (2009) Early implicit contextual change detection in anterior prefrontal cortex. *Brain Res.* 1263, 87–92
- 70 Peterson, M.S. and Kramer, A.F. (2001) Contextual cuing reduces interference from task-irrelevant onset distractors. *Vis. Cogn.* 8, 843–859
- 71 Tseng, Y.-C. and Li, C.-S.R. (2004) Oculomotor correlates of context-guided learning in visual search. *Percept. Psychophys.* 66, 1363–1378
- 72 Zhao, G. *et al.* (2012) Dual-state modulation of the contextual cuing effect: Evidence from eye movement recordings. *J. Vis.* 12, 11
- 73 Ono, F. *et al.* (2005) Intertrial temporal contextual cuing: association across successive visual search trials guides spatial attention. *J. Exp. Psychol. Hum. Percept. Perform.* 31, 703–712
- 74 Jiang, Y.V. *et al.* (2013) The time course of attentional deployment in contextual cuing. *Psychon. Bull. Rev.* 20, 282–288
- 75 Logan, G.D. (1988) Toward an instance theory of automatization. *Psychol. Rev.* 95, 492–527
- 76 Feldmann-Wüstefeld, T. and Schubö, A. (2014) Stimulus homogeneity enhances implicit learning: evidence from contextual cuing. *Vis. Res.* 97, 108–116
- 77 Musz, E. *et al.* (2015) Visual statistical learning is not reliably modulated by selective attention to isolated events. *Atten. Percept. Psychophys.* 77, 78–96
- 78 Manginelli, A. *et al.* (2012) Visual search facilitation in repeated displays depends on visuospatial working memory. *Exp. Psychol.* 59, 47–54
- 79 Travis, S.L. *et al.* (2013) On the role of working memory in spatial contextual cuing. *J. Exp. Psychol. Learn. Mem. Cogn.* 39, 208–219
- 80 Jiang, Y. and Leung, A.W. (2005) Implicit learning of ignored visual context. *Psychon. Bull. Rev.* 12, 100–106
- 81 Jiang, Y. and Song, J.-H. (2005) Hyperspecificity in visual implicit learning: learning of spatial layout is contingent on item identity. *J. Exp. Psychol. Hum. Percept. Perform.* 31, 1439–1448
- 82 Perruchet, P. and Vinter, A. (1998) PARSER: a model for word segmentation. *J. Mem. Lang.* 39, 246–263
- 83 Gobet, F. *et al.* (2001) Chunking mechanisms in human learning. *Trends Cogn. Sci.* 5, 236–243
- 84 Bellaera, L. *et al.* (2014) When being narrow minded is a good thing: locally biased people show stronger contextual cuing. *Q. J. Exp. Psychol. (Hove)* 67, 1242–1248
- 85 Davoli, C.C. *et al.* (2012) A bias to detail: how hand position modulates visual learning and visual memory. *Mem. Cognit.* 40, 352–359
- 86 Goujon, A. *et al.* (2009) Semantic contextual cuing and visual attention. *J. Exp. Psychol. Hum. Percept. Perform.* 35, 50
- 87 Annac, E. *et al.* (2013) Memory under pressure: secondary-task effects on contextual cuing of visual search. *J. Vis.* 13, 6
- 88 Chun, M.M. and Jiang, Y. (1999) Top-down attentional guidance based on implicit learning of visual covariation. *Psychol. Sci.* 10, 360–365
- 89 Endo, N. and Takeda, Y. (2004) Selective learning of spatial configuration and object identity in visual search. *Percept. Psychophys.* 66, 293–302
- 90 Goujon, A. *et al.* (2007) Contextual cuing based on specific and categorical properties of the environment. *Vis. Cogn.* 15, 257–275
- 91 Olson, I.R. and Chun, M.M. (2001) Temporal contextual cuing of visual attention. *J. Exp. Psychol. Learn. Mem. Cogn.* 27, 1299
- 92 Goujon, A. (2011) Categorical implicit learning in real-world scenes: evidence from contextual cuing. *Q. J. Exp. Psychol. (Hove)* 64, 920–941
- 93 Ziori, E. and Dienes, Z. (2012) The time course of implicit and explicit concept learning. *Conscious. Cogn.* 21, 204–216
- 94 Brady, T.F. and Oliva, A. (2008) Statistical learning using real-world scenes extracting categorical regularities without conscious intent. *Psychol. Sci.* 19, 678–685
- 95 Brockmole, J.R. and Henderson, J.M. (2006) Using real-world scenes as contextual cues for search. *Vis. Cogn.* 13, 99–108
- 96 Goujon, A. *et al.* (2014) The emergence of explicit knowledge from implicit learning. *Mem. Cognit.* 42, 225–236
- 97 Goujon, A. *et al.* (2012) How visual and semantic information influence learning in familiar contexts. *J. Exp. Psychol. Hum. Percept. Perform.* 38, 1315–1327
- 98 Brockmole, J.R. *et al.* (2006) Contextual cuing in naturalistic scenes: global and local contexts. *J. Exp. Psychol. Learn. Mem. Cogn.* 32, 699–706
- 99 Ehinger, K.A. and Brockmole, J.R. (2008) The role of color in visual search in real-world scenes: Evidence from contextual cuing. *Percept. Psychophys.* 70, 1366–1378
- 100 Brockmole, J.R. and Henderson, J.M. (2006) Recognition and attention guidance during contextual cuing in real-world scenes: evidence from eye movements. *Q. J. Exp. Psychol. (Hove)* 59, 1177–1187
- 101 Rosenbaum, G.M. and Jiang, Y.V. (2013) Interaction between scene-based and array-based contextual cuing. *Atten. Percept. Psychophys.* 75, 888–899
- 102 Chua, K.-P. and Chun, M. (2003) Implicit scene learning is viewpoint dependent. *Percept. Psychophys.* 65, 72–80
- 103 Kawahara, J. (2003) Contextual cuing in 3D layouts defined by binocular disparity. *Vis. Cogn.* 10, 837–852
- 104 Nabeta, T. *et al.* (2003) Transfer of spatial context from visual to haptic search. *Perception* 32, 1351–1358

- 105 Huang, L. (2006) Contextual cuing based on spatial arrangement of color. *Percept. Psychophys.* 68, 792–799
- 106 Bertels, J. et al. (2012) How implicit is visual statistical learning? *J. Exp. Psychol. Learn. Mem. Cogn.* 38, 1425
- 107 Turk-Browne, N.B. et al. (2008) Multidimensional visual statistical learning. *J. Exp. Psychol. Learn. Mem. Cogn.* 34, 399–407
- 108 Makovski, T. and Jiang, Y.V. (2009) Contextual cost: when a visual-search target is not where it should be. *Q. J. Exp. Psychol. (Hove)* 63, 216–225
- 109 Endo, N. and Takeda, Y. (2005) Use of spatial context is restricted by relative position in implicit learning. *Psychon. Bull. Rev.* 12, 880–885
- 110 Jiang, Y. and Song, J.-H. (2005) Spatial context learning in visual search and change detection. *Percept. Psychophys.* 67, 1128–1139
- 111 Conci, M. and von Mühlenen, A. (2011) Limitations of perceptual segmentation on contextual cueing in visual search. *Vis. Cogn.* 19, 203–233
- 112 Bennett, I.J. et al. (2009) An abbreviated implicit spatial context learning task that yields greater learning. *Behav. Res. Methods* 41, 391–395
- 113 Zellin, M. et al. (2013) Here today, gone tomorrow – adaptation to change in memory-guided visual search. *PLoS ONE* 8, e59466
- 114 Conci, M. et al. (2011) Contextual remapping in visual search after predictable target-location changes. *Psychol. Res.* 75, 279–289
- 115 Masquelier, T. et al. (2008) Spike timing dependent plasticity finds the start of repeating patterns in continuous spike trains. *PLoS ONE* 3, e1377
- 116 Masquelier, T. et al. (2009) Competitive STDP-based spike pattern learning. *Neural Comput.* 21, 1259–1276
- 117 Bertels, J. et al. (2015) Visual statistical learning in children and young adults: how implicit? *Front. Psychol.* 5, 1541
- 118 Turk-Browne, N.B. et al. (2010) Implicit perceptual anticipation triggered by statistical learning. *J. Neurosci.* 30, 11177–11187
- 119 Arciuli, J. et al. (2014) Statistical learning under incidental versus intentional conditions. *Front. Psychol.* 5, 747
- 120 Pacton, S. and Perruchet, P. (2008) An attention-based associative account of adjacent and nonadjacent dependency learning. *J. Exp. Psychol. Learn. Mem. Cogn.* 34, 80
- 121 Conway, C.M. and Christiansen, M.H. (2006) Statistical learning within and between modalities pitting abstract against stimulus-specific representations. *Psychol. Sci.* 17, 905–912
- 122 Otsuka, S. et al. (2014) Constraint on the semantic flexibility in visual statistical learning. *Vis. Cogn.* 22, 865–880