Review

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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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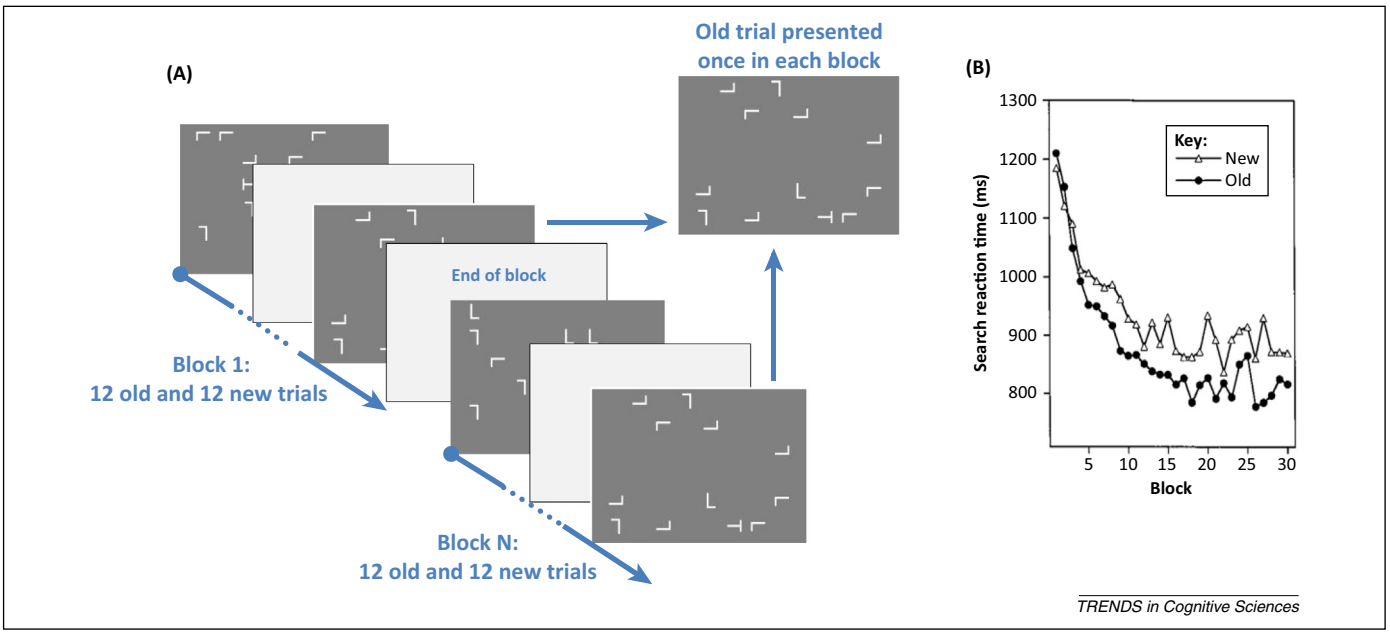

Figure 1. Typical CC task. **(A)** Typical procedure for CC. The task is to search for a rotated T-target among L-distractors. In the typical search task, participants are exposed to a large number of blocks of trials (e.g., 30). Each block usually includes 12 different 'old configurations' that are 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