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Abstract

Can people learn complex information without conscious awareness? Implicit learning—learning without awareness of what has been learned—has been the focus of intense investigation over the last 50 years. However, it remains controversial whether complex knowledge can be learned implicitly. In the research reported here, we addressed this challenge by asking participants to differentiate between sequences of symbols they could not perceive consciously. Using an operant-conditioning task, we showed that participants learned to associate distinct sequences of crowded (nondiscriminable) symbols with their respective monetary outcomes (reward or punishment). Overall, our study demonstrates that sensitivity to sequential regularities can arise through the nonconscious temporal integration of perceptual information.

Keywords

subliminal perception, learning, decision making, rewards, punishment

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The human brain is an incredibly plastic organ that constantly changes in response to its environment. These changes often involve simple forms of learning, such as Pavlovian and operant conditioning, through which an organism becomes sensitive to the associations that exist between two stimuli or between a particular stimulus and the appropriate response. Such changes may also involve more complex forms of learning, such as sensitivity to sequential information and to abstract relationships, as is the case for natural-language learning. Well-known neural mechanisms that involve the creation and modification of synaptic connections (e.g., Hebbian learning) underlie simple learning, which is thus usually assumed to occur independently of conscious awareness of what has been learned. Consistent with this view, studies have shown that stimulus-stimulus and stimulus-response conditioning (i.e., Pavlovian and operant conditioning) can take place with stimuli that are rendered invisible through masking (Pessiglione et al., 2008) or through binocular rivalry (Raio, Carmel, Carrasco, & Phelps, 2012; Seitz, Kim, & Watanabe, 2009).

However, although it is now relatively clear (but see Lovibond & Shanks, 2002) that simple associations can be learned in the absence of awareness, recent theoretical accounts and empirical results challenge the idea that nonconscious learning can take place with complex material as well. In theory, extracting higher-order knowledge (e.g., abstract rules) from a sequence of discrete events requires the active maintenance and integration of perceptual information over time, a process that is typically assumed to require awareness (Dehaene & Changeux, 2011). Thus, it seems somewhat unlikely that sequences of nonconscious stimuli can be learned. Conversely, demonstrating

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the existence of such a phenomenon would suggest that temporal integration extends to nonconscious processes. Decades of empirical research on implicit learning using artificial grammars (Reber, 1967) or sequence-learning tasks (Nissen & Bullemer, 1987) have failed to convince skeptics (e.g., Shanks, 2010; Shanks & St. John, 1994) that complex learning can take place without awareness. This stems essentially from the fact that it is impossible to turn awareness off. In other words, participants will always look for regularities when exposed to visible material, and they will often succeed in finding at least a few. However, the systematic correlation between learning and rule awareness does not necessarily imply that nonconscious learning of complex regularities is impossible. Indeed, the mechanisms that underlie learning in implicit-learning tasks may actually operate nonconsciously, but the resulting knowledge remains accessible through memory recall, even when this takes place incidentally. Thus, even though sophisticated methods have been proposed to address the methodological conundrum of identifying the respective contributions of conscious and nonconscious-learning mechanisms in such situations (Cleeremans & Jiménez, 1998; Destrebecqz & Cleeremans, 2001; Dienes & Berry, 1997), establishing that learning is genuinely implicit remains a formidable challenge.

In the present study, we proposed to solve this problem in a novel manner: We simply asked whether sequence learning can take place when stimuli cannot be consciously perceived. To do so, we used gaze-contingent crowding (Faivre & Kouider, 2011; Kouider, Berthet, & Faivre, 2011), in which flanker-surrounded stimuli are presented in the periphery of the visual field as long as participants keep gazing at a predefined, distinct location. This method makes it possible to expose participants to long-lasting and dynamic stimuli while ensuring that they cannot foveate them (i.e., fixate them in the fovea, which is the part of the retina that gives the best resolution), thus keeping the stimuli out of conscious awareness. We combined this method with a go/no-go operant-conditioning task (Pessiglione et al., 2008) that involved discriminating between two crowded sequences of symbols associated with opposite results: One sequence always predicted a monetary reward, and the other always predicted a monetary punishment (Fig. 1). Our findings showed that participants' decisions were influenced by the monetary values of the crowded sequences, which provides evidence for a nonconscious form of sequence learning.

Method

Participants

Fifty-five college students (age range = 18–35 years; 28 in Paris, 27 in Brussels) participated in the experiment. They reported normal or corrected-to-normal vision and were paid €15 for their participation.

Stimuli and procedure

Stimuli were displayed on a 22-in. CRT computer monitor (resolution = 1,024 × 768 pixels; refresh rate = 85 Hz; Vision Master Pro 510, iiyama, Iiyama, Japan) and were controlled using Psychophysics Toolbox software (Brainard, 1997; Pelli, 1997). Eye movements were recorded monocularly with an EyeLink 1000 eye tracker (sampling rate = 1000 Hz, spatial resolution ≥ 1° of visual angle; SR Research, Mississauga, Ontario, Canada).

On each trial, participants saw one of two sequences that consisted of four repetitions of three different symbols ("O," "=," and "X"). One order of these three symbols was associated with a monetary reward (i.e., the reward sequence); the reverse order was associated with a monetary punishment (i.e., the punishment sequence). Both sequences could begin with any symbol, so neither single symbols nor specific symbol-position associations were predictive of the outcome. The order in which the symbols were presented in the reward and punishment conditions was counterbalanced across participants.

Stimuli were presented in a white typeface against a black background at a viewing distance of 57 cm. Each trial began with a fixation cross (subtending 1.44° × 1.44°) presented at the top of the screen for 500 ms. The 12 symbols (each subtending 1.44° × 1.44°) were then presented successively at the bottom of the screen. The distance between the center of the fixation cross and the center of the symbol was 15°. Each symbol appeared for 153 ms and was separated from the next symbol by a blank screen lasting 94 ms. Each symbol was surrounded by six flankers (1.44° × 1.44°; 1.8° between the center of each symbol and the center of each flanker). We ensured that the three target symbols were matched in luminance by using the same number of pixels in each one. Flankers consisted of a circle overlaid by a central horizontal line and a diagonal line. Participants' eye movements were recorded continuously. Whenever participants' gaze strayed outside a 6° × 6° area surrounding the fixation cross, the target symbol was replaced with a noninformative distractor during the next screen refresh; this procedure ensured that the target remained unseen even when its location was inadvertently or intentionally fixated.

The learning task was adapted from Pessiglione et al. (2008) and involved choosing a go or no-go response on each trial. The period during which a response would be accepted (indicated by the appearance of a red question mark in place of the fixation cross) began at the onset of the fourth symbol (i.e., at the beginning of the second presentation of the sequence) and ended 1,000 ms after the offset of the last symbol. The red question mark was

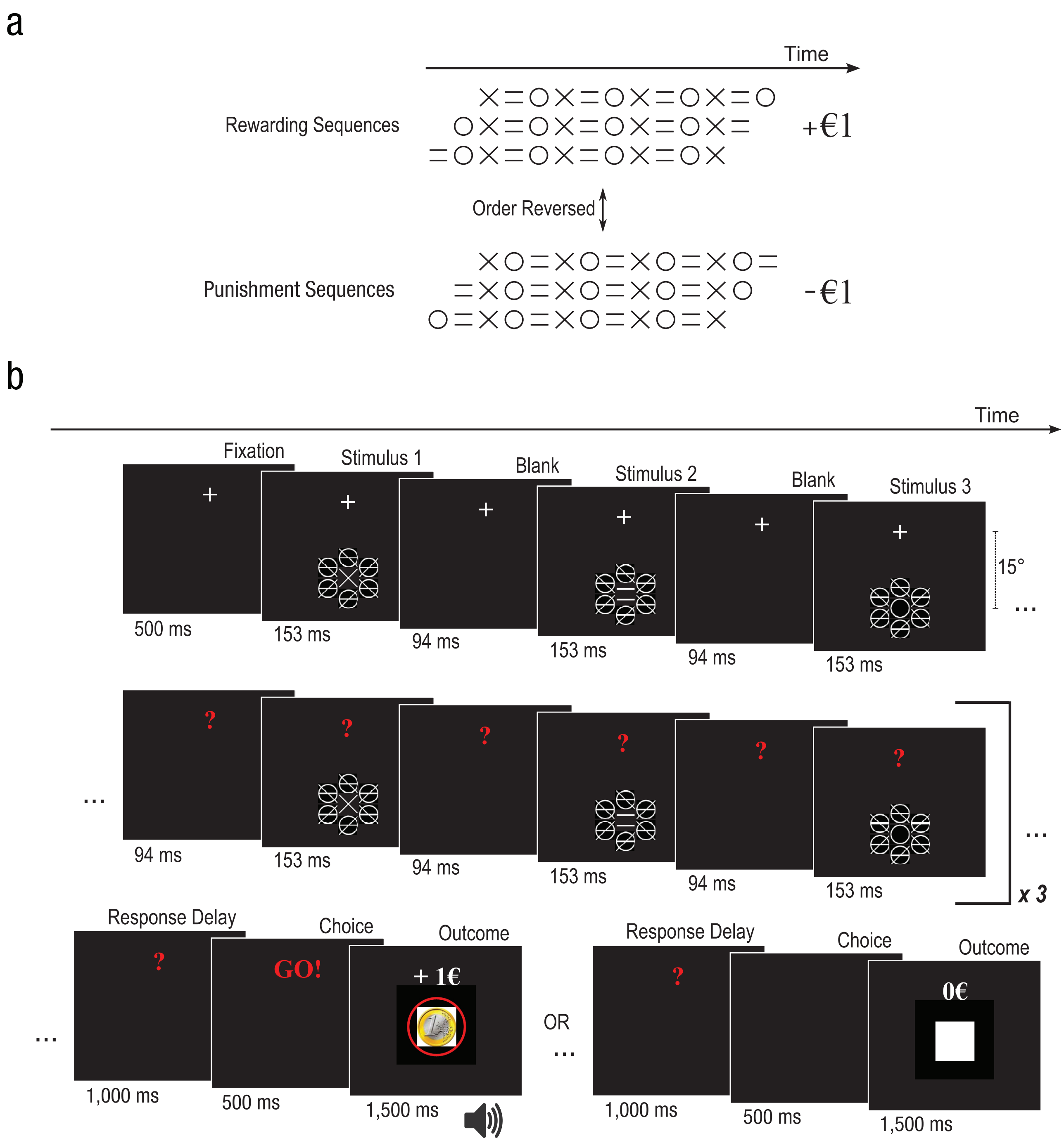

Fig. 1. Stimulus sequences (a) and example trial structure for the reward sequence (b). Reward and punishment sequences consisted of a succession of three different symbols ("O," "=," and "X"), presented four times on each trial. Symbols were always presented in the same order in each type of sequence, but the starting symbol varied. Reward sequences were associated with a gain of €1; punishment sequences were associated with a loss of €1. Regardless of the sequence presented, each trial began with a fixation cross, and then a symbol appeared toward the bottom of the screen surrounded by flankers. Twelve symbols were presented successively, each separated by a blank screen. At the onset of the fourth symbol, a question mark replaced the fixation cross for the remainder of the trial to indicate that participants could now choose at any time to make a go response (in which they would win €1 or lose €1) or make no response (i.e., a no-go response, in which they would neither win nor lose). Participants were required to stare at the fixation cross so the stimulus sequence would remain in their peripheral vision. After the last stimulus had been presented on each trial, the red question mark remained on screen for 1,000 ms. On trials on which participants responded "go," the word "GO!" replaced the question mark. They then saw either reward information if a reward sequence had been presented on that trial (shown at the bottom left) or punishment information if a punishment sequence had been presented on that trial (not shown). On trials on which they made no response, they were given neutral information and no reward (shown at the bottom right).

thus presented for approximately 3,150 ms. Participants were instructed to make their choice at any time during that period by either holding down the space bar until the end of the response delay (the go response) or doing nothing (the no-go response). Participants were informed that the go response was risky because they could win or lose €1 depending on whether the presented sequence was the reward or the punishment sequence, respectively. By contrast, no-go responses were always associated with a null reward (€0) and thus constituted a safe choice for participants. On go trials, participants' choice was confirmed after the response delay by the appearance on the screen of "GO!" in a red typeface (500 ms). The screen remained blank during this time period on no-go trials. The monetary outcome was then presented for 1,500 ms. If the participant had responded to a reward sequence, an image of a coin in a circle appeared on the screen accompanied by a slot-machine sound, which let the participant know that €1 had been added to his or her total. If the participant had responded to a punishment sequence, an image of a crossed-out coin appeared on the screen accompanied by a buzzer sound, which let the participant know that €1 had been subtracted from his or her total. If the participant had not responded (i.e., no go), a white square appeared on the screen and no sound was generated, which let the participant know that no money had been added to or subtracted from his or her total.

The learning task consisted of 180 trials grouped in three blocks of 60 trials each, separated by short breaks. Within each block, the reward sequence was presented in half of the trials, and the punishment sequence was presented in the other half; the trial types were intermixed randomly. We encouraged participants to learn to differentiate the two sequences as best they could to increase their gains. Because covert attention is known to enhance the influence of crowded signals (Faivre & Kouider, 2011), we instructed the participants to stare at the fixation cross while simultaneously paying attention to the symbol location and to try to guess whether the crowded stimulus cluster contained the reward or punishment sequence. We told them that the task was difficult and that they should rely on intuition and their gut feeling. We also told them that they could make their go/no-go decision either during or after the sequence presentation, and we encouraged them to make this decision as soon as they felt they had accrued enough evidence about the sequence. To further motivate participants, we told them that their performance could result in a total monetary bonus ranging from €0 to €5. However, all participants eventually received the maximum bonus of €5.

The learning task was followed by a visibility task involving one block of 72 trials. Participants were exposed to the same sequences of crowded stimuli as during the learning task. After the last peripheral symbol, a question mark accompanied by the foveal presentation of four symbols (aligned horizontally and in either the reward or the punishment sequence) was displayed until a response was made. Participants were instructed to decide whether the succession of four symbols were in the same order as the peripheral sequence that had been presented in that trial.

Results

We analyzed only trials for which gaze position remained at fixation during 90% of the sequence duration, which resulted in the elimination of 7.9% (*SD* = 16.3%) of the trials. On average, participants chose the risky go response in 60.3% (*SD* = 11.4%) of the trials. We first analyzed go versus no-go choices. To do so, we computed a decision-bias index by subtracting the average go-response rate for the punishment sequences from the average go-response rate for the reward sequences. This index was not significantly different from 0, $t(54) = 0.86$, $p = .40$; decision-bias index = 0.9% (see Fig. 2a). We then analyzed reaction times (RTs) of the go decision (obviously, no-go decisions did not yield RTs). After excluding outlier data (RTs < 100 ms), the overall mean RT was 1,782 ms (*SD* = 468 ms). Participants' go responses were faster for the reward sequences than for the punishment sequences, $t(54) = 2.75$, $p = .008$; mean difference = 34 ms (see Fig. 2b). The analysis of median RTs showed the same result, $t(54) = 2.71$, $p = .009$; mean difference = 45 ms.

The percentage of responses in the visibility task on which participants correctly identified the sequence of stimuli did not differ from the chance level of 50%, $t(54) = 0.11$, $p = .91$; *M* = 50.12%, which suggests that participants were unable to consciously discriminate the reward sequences from the punishment sequences. Visibility-task performance also failed to correlate with reaction-time differences in the learning task, $r(53) = .19$, $p = .16$, which again suggests that participants' learning was independent of their ability to consciously discriminate the sequences. Finally, mean RTs were not different between the reward and punishment sequences in the visibility task, $t(54) = 0.61$, $p = .545$; mean difference = 26 ms. Furthermore, we conducted an analysis of variance investigating the effect of accuracy (trials with correct responses vs. trials with incorrect responses) and sequence (reward vs. punishment) on mean RTs, but the interaction between the two independent variables was not significant, $F(1, 54) = 0.78$, $p = .381$. This interaction was still not significant when we excluded RTs lower than 100 ms and more than 3 standard deviations from the mean, $F(1, 54) = 0.71$, $p = .402$, or used the median RTs, $F(1, 54) = 0.151$, $p = .699$. The difference between RTs for correct responses in each sequence type was 1 ms for the analysis without cutoff, −20 ms for the analysis with cutoff, and

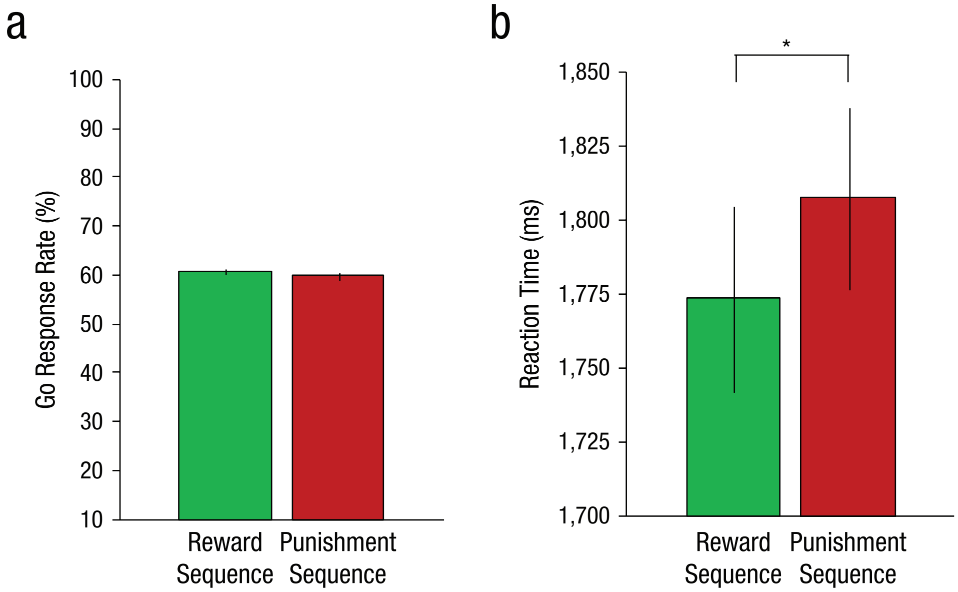

Fig. 2. Mean rate of go responses (a) and mean reaction time for go responses (b) in the learning task as a function of sequence type. Error bars represent ±1 *SE*. The asterisk indicates a significant difference between conditions ($^*p < .01$).

−16 ms for the analysis on medians. Thus, the RTs collected during the visibility task most likely reflected noisy fluctuations. This suggests that the facilitatory effect on RTs for the reward sequence was specific to the learning task.

Discussion

In the present study, we explored whether participants could learn a sequence of stimuli that they could not consciously perceive. To do so, we used (a) a gaze-contingent crowding paradigm that enabled the long-lasting and dynamic presentation of nonconscious signals and (b) an operant-conditioning task in which participants had to choose to respond or not (go/no-go) on the basis of the monetary value associated with the crowded stimuli. We showed that participants gave go responses faster to the reward sequence than to the punishment sequence, whereas awareness measures indicated that the sequences were not consciously discriminable from each other. Our results thus demonstrate (a) that sensitivity to sequential regularities can take place even when the sequences of stimuli themselves are not perceived consciously and (b) that the temporal integration necessary for sequence learning to occur can take place in a nonconscious manner.

The nonconscious-learning effect we found is likely to depend on a combination of perceptual sequence learning (i.e., linking successive stimuli together) and of operant conditioning (i.e., linking each visual sequence to either an action leading to a reward or an action leading to an avoidance of punishment). The large literature on incidental sequence learning (for reviews, see Clegg, DiGirolamo, & Keele, 1998; Robertson, 2007) indeed suggests that participants can become sensitive to the sequential structure of visible stimuli despite limited awareness of the sequential regularities. The present study shows that perceptual sequence learning can also occur without awareness of the stimuli, at least when the task is intentional, as was the case here. Indeed, participants were informed about the presence of two different sequences of symbols and were also instructed to pay attention to the symbols and their order. Although covert attention to subthreshold crowded stimuli crucially enhances their influence on behavior (Faivre & Kouider, 2011), whether an explicit learning context was necessary in the current paradigm remains unknown. Previous studies have shown that reward or fear conditioning can occur even when the conditioned stimulus is presented nonconsciously (Pessiglione et al., 2008; Raio et al., 2012; Seitz et al., 2009). Our study extends previous findings by showing that conditioning can also be based on the extraction of knowledge from sequences of nonconscious stimuli.

Although our participants unmistakably acquired some form of sequential knowledge, the exact nature of this knowledge remains unclear. Indeed, although the results cannot be explained in terms of simple stimulus-reward associations, extracting only the order of two successive symbols (e.g., "XO" vs. "OX") may be sufficient for participants to differentiate between the reward and the punishment sequences. It remains unclear whether the learning effects we report arose from processing all the sequential information or from processing only two successive symbols. In either case, the structure of the sequences we used, in which a symbol can fully predict the subsequent one (i.e., a so-called first-order sequence), limits learning to the acquisition of basic sequential knowledge. Whether learning of more elaborate sequences (e.g., the second-order conditional sequences typically used in implicit-learning tasks) can occur without perceptual awareness remains to be explored.

The nonconscious-learning effect we observed was reflected primarily in RTs rather than in response biases. There are for two possible reasons for this. First, nonconscious stimuli have only a weak impact on behavior; they can certainly influence RTs but are not strong enough to affect overt responses (for a review, see Kouider & Dehaene, 2007). The absence of a nonconscious perceptual effect on response performance is reported not only in indirect tasks (e.g., priming tasks, Custers & Aarts, 2011; Kouider & Dehaene, 2007) but also in more direct tasks (e.g., go/no-go tasks; van Gaal, Ridderinkhof, Scholte, & Lamme, 2010). In our learning task, the nonconscious sequential signal might delay or accelerate the decision process in relation to the expected monetary value (reward or punishment, respectively) but may not be strong enough to bias the overt decision of gambling. Although Pessiglione et al. (2008) found an effect on response performance using exactly the same direct task, their participants' decisions were based on a single stimulus, which probably made the decision easier. Second, we found a negative correlation between overall response rate (i.e., the rate of go responses independent of which sequence had been presented) and learning effect for both RTs and responses (see the Supplemental Material available online). This correlation indicates that participants who chose the go response less frequently showed strong sequence learning, not only for response latencies but also for overt decision-making performance, whereas participants who chose the go response more frequently exhibited no learning effect. Thus, learning on response bias might also occur, but it would to depend on the frequency with which a participant chose the go response.

Previous research suggests that active maintenance and serial integration of sensory information are characteristic of conscious perceptual processes (e.g., Dehaene & Changeux, 2011). Indeed, past studies have revealed that although masked stimuli can effectively prime behavior, such influences are usually short-lived and vanish after a mere few hundred milliseconds (Dupoux, de Gardelle, & Kouider, 2008; Ferrand, 1996; Greenwald, Draine, & Abrams, 1996). Along the same lines, it has been shown that serial processing (i.e., chaining two successive operations) is restricted to conscious perception (Sackur & Dehaene, 2009). Here, by contrast, we found that crowded symbols presented in temporal succession can influence reward-based decision making, which suggests that the activation of each element is maintained and integrated over time. Recently, de Lange, van Gaal, Lamme, and Dehaene (2011) studied the impact of visibility on temporal integration. They compared the accumulation of sequential evidence under conditions of high versus low visibility and found that the degree of visibility did not matter. Both situations, however, involved stimuli presented above the threshold of conscious awareness. Our study thus extends this finding to nonconscious perceptual conditions. The present sequential integration of nonconscious information was demonstrated through a crowding paradigm. Crowding is more likely than masking to involve weaker signal degradation and to result in stronger activation at deeper levels of representation (e.g., semantic or emotional representations; Faivre, Berthet, & Kouider, 2012). Thus, it is possible that the previously observed limitations in the processing of nonconscious information are inherent to masking rather than to the cognitive system. Likewise, our findings support a late origin of crowding along the visual pathways (He, Cavanagh, & Intriligator, 1996), which is consistent with recent studies revealing emotional bias from crowded faces (Kouider et al., 2011) and semantic priming from crowded words (Yeh, He, & Cavanagh, 2012).

Overall, the present study extended the current known limits of nonconscious processing by showing that participants can become sensitive to the sequential regularities embedded in series of crowded symbols that are not consciously accessible. Our study thus challenges the idea that the temporal integration necessary for sequence learning is restricted to conscious processing. Further research is needed to document the limits of nonconscious processing with this kind of material. For instance, one might now ask whether more complex learning that involves sensitivity to abstract relationships, such as in artificial grammar learning, could also be learned under conditions in which the stimuli themselves are not perceived consciously. Gaze-contingent crowding, which makes it possible to present stimuli for a long duration while ensuring that they remain out of awareness, will undoubtedly prove to be a valuable tool in this endeavor.

Author Contributions

S. Kouider, A. Atas, and N. Faivre designed the study. A. Atas conducted the experiment and analyzed the data. A. Atas, S. Kouider, and A. Cleeremans wrote the manuscript. N. Faivre and B. Timmermans provided critical input.

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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Supplemental Material

Additional supporting information may be found at http://pss.sagepub.com/content/by/supplemental-data.

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