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Short Communication

# Detecting conscious awareness from involuntary autonomic responses

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ABSTRACT

Can conscious awareness be ascertained from physiological responses alone? We evaluate a novel learning-based procedure permitting detection of conscious awareness without reliance on language comprehension or behavioural responses. The method exploits a situation whereby only consciously detected violations of an expectation alter skin conductance responses (SCRs). Thirty participants listened to sequences of piano notes that, without their being told, predicted a pleasant fanfare or an aversive noise according to an abstract rule. Stimuli were presented without distraction (attended), or while distracted by a visual task to remove awareness of the rule (unattended). A test phase included occasional violations of the rule. Only participants attending the sounds reported awareness of violations and only they showed significantly greater SCR for noise occurring in violation, vs. accordance, with the rule. Our results establish theoretically significant dissociations between conscious and unconscious processing and furnish new opportunities for clinical assessment of residual consciousness in patient populations.



## 1. Introduction

An important challenge for cognitive psychology, neuroscience, and clinical neurology is to determine whether conscious awareness can be detected through non-behavioural responses. From a theoretical perspective, any method allowing the conscious status of knowledge to be assessed without the confounding influence of explicit subjective reports is of considerable value. More urgently, the assessment of consciousness in brain injured patients is central to the differential diagnosis of vegetative state, minimally conscious state, and locked-in syndrome. Accurate diagnosis is needed to inform prognosis and clinical management (Jennett, 2002). Current clinical practise relies heavily on behavioural evaluation and is therefore limited where volitional motor responses or language comprehension are compromised (Majerus, Gill-Thwaites, Andrews, & Laureys, 2005). These limitations contribute to rates of misdiagnosis, estimated to be 37–43% in patients diagnosed as vegetative state (Andrews, Murphy, Munday, & Littlewood, 1996; Childs, Mercer, & Childs, 1993; Schnakers et al., 2009).

A variety of methods have been developed to aid evaluation of behaviourally unresponsive patients. Electrophysiological and nuclear medicine techniques have established power for predicting negative outcome (Carter & Butt, 2005; Daltrozzo, Wioland, Mutschler, & Kotchoubey, 2007). In contrast, detecting the presence of residual consciousness as a means to predict positive outcome, remains a substantial challenge.

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Cognitive theories and empirical research have motivated a number of candidate methods. One approach draws on an apparent awareness-dependence for trace vs. delay conditioning. In trace conditioning the CS ends prior to the US, thus requiring a memory 'trace' for an association to be made, while in delay conditioning the CS and US overlap. Several studies have found that trace but not delay conditioning requires awareness of the stimuli and of the associative relationship (Knight, Nguyen, & Bandettini, 2006; Lovibond & Shanks, 2002), though others have failed to observe this limitation to unconscious learning (Destrebecqz et al., 2010; Fu, Fu, & Dienes, 2008). Bekinschtein, Shalom et al. (2009) employed trace conditioning of the eye-blink response evaluating anticipatory electromyographical responses as an indicator of learning. While they observed that the degree of learning was a good indicator of recovery in patients, the method failed to provide a clean separation of conscious and unconscious control subjects; some conscious controls failed to learn and one unconscious control showed marginal learning while under general anaesthetic.

A related approach exploits cognitive event-related potentials (ERPs) to detect awareness of violations in temporal regularities. Bekinschtein, Dehaene et al. (2009) devised a paradigm with both local and global violations of an auditory regularity such that detecting the global differences required maintaining the perceptual representation over some seconds, which was held to require consciousness. Consistent with their predictions only the global violations generated a P300 ERP complex previously associated with conscious access (Sergent, Baillet, & Dehaene, 2005), and this effect was only present in participants reporting awareness of the global structure. However, the effect was only reliably observed in participants instructed to attend to the global regularity. The method is consequently dependent on verbal comprehension which is known to be impaired in a significant proportion of stroke and traumatic brain injury patients (Eisenberg et al., 1990; Inatomi et al., 2008).

Finally, an alternative approach employs functional neuroimaging to index distinct patterns of regional brain activity associated with the content of intentional visual imagery. This method has provided evidence for conscious awareness in patients otherwise fulfilling the criteria for vegetative state (Monti et al., 2010; Owen et al., 2006). However, in addition to requiring brain-imaging equipment, the method is again reliant on verbal comprehension; patients must change their mental imagery in accordance with verbal instructions.

Despite these advances, there remains a need for an accurate method to determine conscious awareness, that is not reliant on motor responses or language comprehension, and which preferably can be applied at the bedside. To address this challenge we devised a novel approach which we term the Learned Aversive Contingency (LAC) procedure. The method exploits the skin conductance response (SCR) to index learning of a predictive relationship. Specifically, sequences of piano notes predicted either a pleasant fanfare or aversive white noise. Patients diagnosed as persistent vegetative state (PVS) are known to exhibit significant SCRs in response to white noise (Hildebrandt, Zieger, Engel, Fritz, & Bussmann, 1998; Keller, Hulsdunk, & Muller, 2007), making this a suitable clinical measure. The predictive sequences were designed to minimise the likelihood of unconscious learning. In common with previous attempts, a delay was inserted between the predictive sequence and the aversive or non-aversive stimulus. However, based on evidence that the proportion of unconscious learning reduces with longer delays (e.g. Kuhn & Dienes, 2005; Kuhn & Dienes, 2006) we inserted an extended pause of between 1 and 2 s during training and always 2 s during testing – four times that commonly used in trace conditioning. In addition, the predictive rule was abstract in nature; the pattern of similarity between the notes predicted the outcome but the pitch of the notes was different in every test sequence. Implicit learning of this type of consistency, known as repetition structure, can be observed in paradigms such as artificial grammar learning (AGL), where its influence is mediated by feelings of familiarity (Scott & Dienes, 2008, 2010a; but not by fluency, Scott & Dienes, 2010b). However, the learning context in paradigms such as AGL is substantially different to that employed in the current study. Most notably, in AGL all elements of the stimuli are typically presented either simultaneously as a single visual unit, or as an uninterrupted stream. In the present auditory paradigm we aimed to reduce implicit learning by a combination of the 2-s delay preceding the final element of each sequence and the use of a unique pitch on each trial.

To measure conscious expectation, we exploited differences in SCR in response to the noise when its occurrence was predictable vs. unpredictable. SCR magnitudes evoked by an aversive stimulus are greater when the stimulus is unanticipated (Ohman, 1971). Learning was therefore assessed by comparing SCR in test trials where the rule either applied as before or was violated such that the aversive noise was unexpected. Critically, we sought to devise a training sequence that made the rule sufficiently salient that individuals attending the sounds would detect it without instruction, thus avoiding dependence on verbal comprehension. We manipulated attention as the means to simulate patients who are either consciously aware or unaware of the auditory structure, thus permitting us to test the extent to which learning is dependent on awareness. While opinions differ as to whether consciousness and attention are doubly dissociable processes (Bussche, Hughes, Humbeeck, & Reynvoet, 2010; Koch & Tsuchiya, 2007), we merely exploited their uncontroversial possible association, and verified the effectiveness of the attention manipulation on conscious awareness of the rule using subjective reports.

We evaluate the LAC procedure by contrasting reported awareness and SCR measurements in participants exposed to the sound sequences without distraction with those of participants engaged in a visual task removing attention from the sounds. Removing awareness in this way has important advantages over alternative approaches, such as the use of anaesthesia (Bekinschtein, Shalom et al., 2009), because unlike those approaches attentional manipulation should not compromise other brain functions possibly preserved in patients.

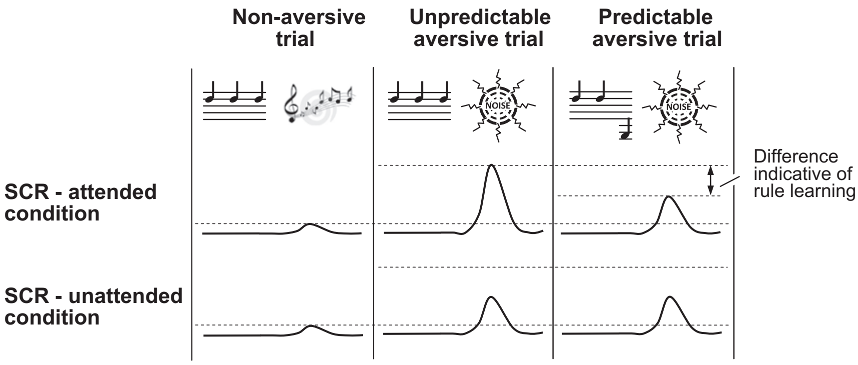


**Fig. 1.** Trial types and predicted SCR. In the attended condition, larger magnitude responses are expected for unpredictable as compared to predictable trials, indicating rule learning. In the unattended condition, this difference is expected to be abolished.

## 2. Material and methods

### 2.1. Participants

Thirty students (11 male, 19 female; age $M = 23$, $SD = 4.1$ years) participated in exchange for course credits or £5. All participants were naive to the experimental hypothesis and were randomly assigned to experimental condition (attended or unattended).[1]

### 2.2. Materials

Sound sequences included 40 training trials and 65 test trials. Each trial consisted of three piano notes followed by a pause (initially 1 s, increasing to 2 s) and either a pleasant fanfare or a burst of white noise (100 dB, 1 s). Two trial types were presented during training: (1) non-aversive trials, consisting of three identical notes followed by the fanfare, and (2) aversive trials, where the third note was substantially different from the previous two and followed by white noise. Training included 15 aversive trials and 25 non-aversive trials arranged to facilitate uninstructed learning of a simple rule: Three identical notes (of any pitch) predicts the pleasant fanfare, whereas a different third note predicts the noise burst.

The test phase consisted of eight blocks of eight trials with the first block preceded by one additional aversive trial. This first aversive trial was included solely to reacclimatise participants to the noise burst after the 5 min of silence following training; this trial was therefore not included in the analyses. Each of the eight blocks contained six non-aversive trials, one predictable aversive trial, and one unpredictable aversive trial, in pseudo-random order. In predictable aversive trials, the noise burst was preceded by a sequence in which the third note was different, as in training. In unpredictable aversive trials, the noise burst occurred after three identical notes, violating the rule. Learning would be apparent as larger magnitude SCRs for unpredictable compared with predictable trials (Fig. 1). The pause between piano notes and fanfare or white noise was 2 s in all test trials. Full details of training and test sequences are given in Tables S1 and S2 of the Supplementary material.

### 2.3. Procedure

Participants were seated at a computer and equipped with headphones. Skin conductance was recorded from electrodes attached to the index and middle fingers of their left hand. Training sequences were followed by a 5 min rest before the test sequences.

The attended condition aimed to simulate conscious patients without motor volition or language comprehension. These participants were therefore asked to imagine they were hospital patients, unable to move or understand language. Care was taken not to provide any verbal or other instruction. The unattended condition aimed to simulate patients lacking conscious awareness of the stimuli. These participants were therefore asked to perform a visual discrimination task as accurately as possible while ignoring the sounds. The visual task involved using eye-movements to indicate the position and orientation of a line appearing on screen (see Fig. S1 in the Supplementary material).

[1] Twenty-four participants were randomly assigned in equal numbers to the two conditions. To replace those not showing sufficient sympathetic response for learning assessment (see results), an additional six were recruited and randomly assigned in appropriate proportions.

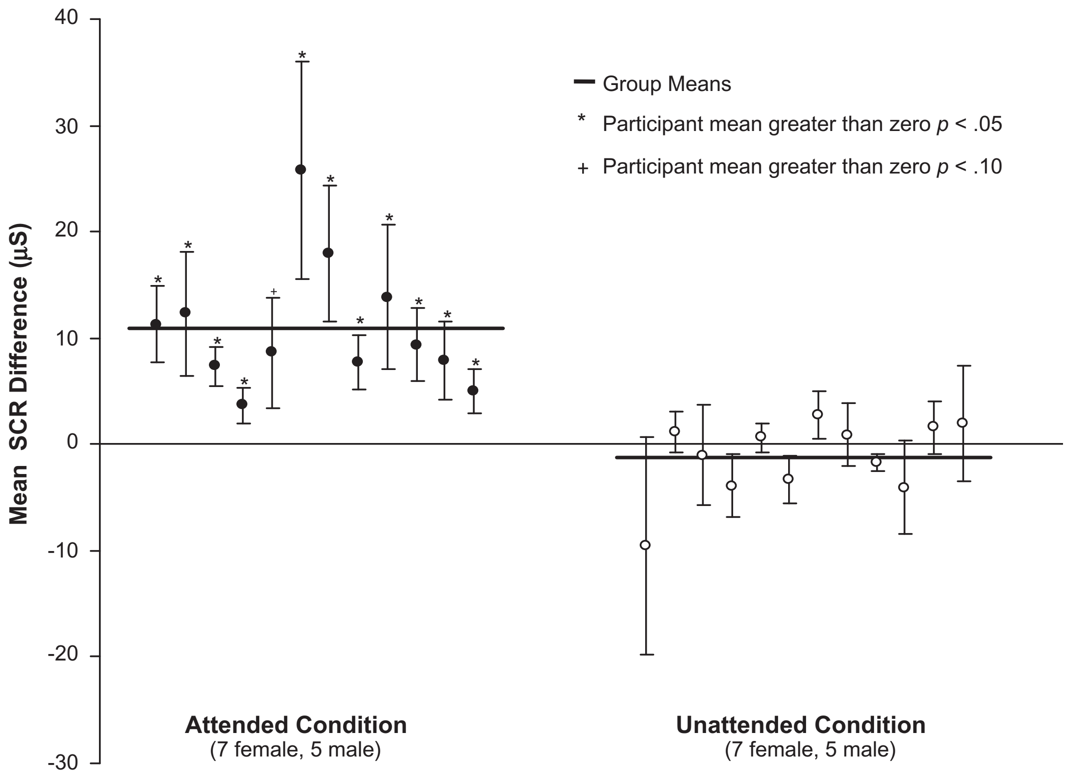


**Fig. 2.** Mean difference in SCR magnitude for unpredictable minus predictable aversive trials, shown for each participant grouped by condition. Error bars indicate standard error of the mean.

## 3. Results

Skin conductance was measured with a sensitivity of 0–100 µS, the signal sampled at 500 Sa/s 16-bit, low-pass filtered at 5 Hz, and detrended with a 15 degree polynomial. For each test trial, the amplitude of SCR evoked by the fanfare or noise burst was determined as the difference between the maximum in the 0–8 s post-stimulus interval and the average in the 1–3 s pre-stimulus interval.

Statistical analysis was performed individually for each participant. First, SCRs with amplitude beyond three standard deviations from the mean for each trial type were excluded as outliers; there were 36 outliers in total, no more than two for any participant, and all were for non-aversive trials.[2] Second, a two-sample *t*-test was performed to verify whether SCR amplitude was greater for noise bursts than fanfares; since the absence of this difference would indicate insufficient sympathetic response to use SCR as a measure of learning, such participants were excluded from further assessment. This represents a practical constraint but also ensures that in clinical application compromised autonomic responsivity would not result in a false negative assessment. In the remaining participants, a paired one-tailed *t*-test assessed whether SCR magnitudes were greater for the eight unpredictable compared with the eight predictable aversive trials.

Upon completion of the experiment, each participant in the attended condition reported learning the rule during the training phase and realising that it was occasionally violated during the test phase. No participant in the unattended condition reported awareness of the relationship between the piano notes and subsequent sounds; as intended, the visual distraction task eliminated conscious awareness of the auditory structure. Six participants (one attended condition, five unattended condition) failed to show significantly greater SCR magnitudes to noise bursts than fanfares and were hence excluded from the subsequent learning assessment.

For the remaining 24 participants (12 per condition) the differences in SCR magnitudes for unpredictable minus predictable aversive trials are shown in Fig. 2. For the attended condition, SCR magnitudes were larger for unpredictable as compared to predictable aversive trials ($M = 20.9$, $SD = 10.8$ µS vs. $M = 11.2$, $SD = 7.8$ µS). This effect was significant at the individual level for eleven participants ($p < .05$) and marginal for one ($p = .071$). In the unattended condition, SCR magnitudes were not larger for unpredictable compared with predictable trials ($M = 4.9$, $SD = 6.2$ µS vs. $M = 6.6$, $SD = 8.3$ µS); the effect

[2] This pattern is to be expected given that there were more non-aversive than aversive trials (48 vs. 16) and that the magnitude of SCRs elicited is smaller for non-aversive than aversive trials. As such, any compromised response, for example resulting from the participant coughing, will have been more likely to occur during a non-aversive trial and would also be more likely to result in an SCR magnitude outside the normal range for non-aversive than aversive trials.

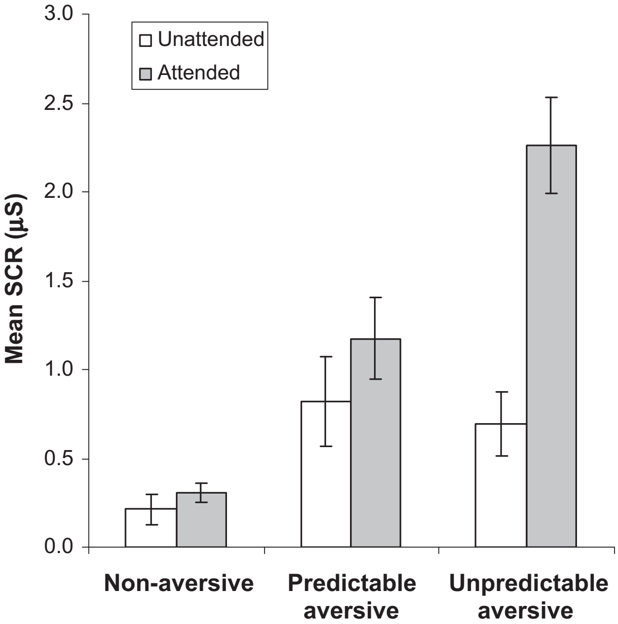


**Fig. 3.** Mean SCR magnitudes for each type of test trial contrasted between attended and unattended conditions. Error bars indicate standard error of the mean.

was not significant at the individual level for any participant (all $p > .13$; 95% CI of the difference −3.4, +1.0 μS, ruling out population differences even remote from the attended mean difference of 10.9 μS).

It was possible that the visual task could have influenced SCR magnitudes in some way other than by the intended influence on awareness of the auditory structure. To test for this we compared the magnitude of the SCRs for each type of test trial, between attended and unattended conditions, see Fig. 3. The magnitudes did not differ between groups for non-aversive trials, $t(22) = .94$, $p = .356$, or predictable aversive trials, $t(22) = 1.03$, $p = .314$, but did so for unpredictable aversive trials, $t(22) = 4.79$, $p < .001$, where, as predicted based on the violation of expectations, SCR magnitudes were significantly greater for the attended condition. There is hence no evidence that the visual task affected SCRs by a means other than the intended influence on awareness.

The results demonstrate that only participants who had conscious awareness of the rule showed a significantly greater SCR magnitude when it was violated. Participants in the unattended condition, all of whom reported being unaware of the rule, showed equivalent SCR magnitudes after white noise irrespective of whether it occurred in accordance or violation of the rule. It is not possible to estimate the extent to which the observed absence of implicit learning was due to any specific feature of the paradigm. However, the results are consistent with both the inclusion of an extended pause prior to the predicted stimulus and the use of different pitches on each trial being effective in reducing unconscious learning.

## 4. Discussion

The results confirm that: (1) the LAC procedure enabled reliable learning of an abstract relation in the absence of any instruction, (2) conscious awareness of the relation was important for learning to occur, and (3) learning was detectable from autonomic responses. The procedure thus provides a means to detect conscious awareness based solely on an autonomic response and avoids reliance on language comprehension or motor responses.

The technical simplicity of the LAC procedure ensures that it could be easily implemented at the bedside, inviting consideration of its clinical potential. Our results suggest the method would have a high diagnostic *specificity*; i.e., it would provide strong evidence for the presence of conscious awareness. This is supported by the fact that removing awareness of the contingency by manipulating attention was sufficient to eliminate learning despite cognitive function being otherwise intact. The procedure should also provide higher *sensitivity* than existing measures because it does not require language comprehension or motor responses. Potential limitations include inadequate cognitive or attentional capacity, which may occur in patients with extensive cortical damage, and compromised autonomic responsivity impairing SCR. While SCRs evoked by white noise are observed in PVS patients (Hildebrandt et al., 1998; Keller et al., 2007) the procedure also embeds a test for these responses, thus allowing identification of patients for whom assessment would be inconclusive. Relevant to both specificity and sensitivity, a recent study found that coma patients have preserved SCR to emotionally salient stimuli (Daltrozzo et al., 2010). The presence of SCR in presumably unconscious patients emphasises the robustness, and hence suitability, of this response, while also highlighting the need to test for learning of an abstract relation to provide specificity.

The absence of a reliable SCR to the white noise observed for five participants in the non-attending condition may in part be due to these participants being required to actively focus their attention on the visual task. This reduced responsivity would not be expected in conscious patients as it is unlikely they would deliberately focus their attention on something other than the sound sequences.

The term consciousness has several meanings (Rosenthal, 2005). For example, there is a distinction between creature consciousness and mental state consciousness. Our method bears only on the latter. That is, our aim is to answer the question: Does the person being assessed have any conscious mental states? By virtue of the empirical reliance that we have demonstrated, namely that under the conditions of our test conscious knowledge is required for learning to be apparent, learning on our test can be taken as evidence for the existence of conscious knowledge. A negative result allows no conclusion as to whether or not the person has any conscious mental states.

During development of our procedure a variety of experimental factors were found to influence the reliability with which attending participants acquired the rule. Multiple revisions of the training sequences were necessary to overcome an apparent *contingency blindness*, whereby seemingly obvious relations were missed in the absence of direct instruction. This phenomenon has parallels with other surprising examples of cognitive opacity including change blindness and inattentional blindness (Simons & Chabris, 1999; Simons & Rensink, 2005) and is it itself worthy of further research. For example, such research could investigate more generally how dissociations between conscious and unconscious processing depend on task instructions and participant expectations, as well as on the details of the stimuli. A summary of all factors observed to influence learning is provided in Supplementary material.

## 5. Conclusion

We have demonstrated how learning of an aversive contingency, assessed by an autonomic response, can be employed to reliably identify conscious awareness independently of language comprehension or motor volition. The LAC procedure advances our understanding of dissociations between conscious and unconscious processing in the absence of explicit instruction. It also has the potential to substantially enhance the clinical assessment of conscious awareness in brain injured patients.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.concog.2010.11.009.

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