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Sequential congruency effects in implicit sequence learning

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ABSTRACT

We deal with situations incongruent with our automatic response tendencies much better right after having done so on a previous trial than after having reacted to a congruent trial. The nature of the mechanisms responsible for these sequential congruency effects is currently a hot topic of debate. According to the conflict monitoring model these effects depend on the adjustment of control triggered by the detection of conflict on the preceding situation. We tested whether these conflict monitoring processes can operate implicitly in an implicit learning procedure, modulating the expression of knowledge of which participants are not aware. We reanalyze recently published data, and present an experiment with a probabilistic sequence learning procedure, both showing consistent effects of implicit sequence learning. Despite being implicit, the expression of learning was reduced or completely eliminated right after trials incongruent with the learned sequence, thus showing that sequential congruency effects can be obtained even when the source of congruency itself remains implicit.

1. Introduction

When an experienced driver corrects the trajectory of a vehicle upon perceiving the cues from a sudden wind gust, or a skater changes slightly her center of gravity in response to subtle irregularities on the floor surface, they are expressing their highly automated knowledge in flexible ways. Indeed, the mark of expertise is not just automatic responding to highly predictable environments, but also fast and flexible adaptations to unpredicted changes (Ericsson, 2006). Implicit learning has often been related with the processes leading to expertise (Cleeremans, Destrebecqz, & Boyer, 1998; Shanks, 2005). However, some researchers have suggested that, in contrast to explicit learning, implicit learning results in a relatively rigid knowledge base, which tends to be applied exclusively in the acquisition context (Abrahamse & Verwey, 2008; Berry & Dienes, 1993), and keeps affecting performance even when its utility decreases over a transfer phase (Jiménez, Vaquero, & Lupiáñez, 2006). According to that description of implicitly acquired knowledge, one may wonder whether it can sustain the flexibility required for expert performance, or whether other forms of knowledge should be responsible for these dynamic adaptation effects. The goal of this study is to assess whether the expression of implicit knowledge can be flexibly adapted to changes in its conditions of application, and precisely whether it can be sensitive to momentary changes in the usefulness of previously acquired tendencies.

2. Implicit sequence learning

Learning in serial reaction time (SRT) tasks has been taken as a lab model of skill acquisition. In the standard versions of this task, participants are required to respond as fast and accurately as possible to each trial by pressing on the key corre-

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sponding to the current location of a stimulus, which appears on each trial at one of a limited number of locations (see Fig. 1, panel A). Unbeknownst to participants, the series of locations follows a relatively complex spatial sequence (for instance, a sequence of 12 trials which is continuously recycled over training, such as those depicted in Fig. 1, panel B). Sequence learning is shown by a progressive improvement in responding to the structured trials (Nissen & Bullemer, 1987), as well as by a cost observed when the stimulus stops following the training sequence and is replaced either by a random trial (Cohen, Ivry, & Keele, 1990) or by a trial generated by a control sequence (Schvaneveldt & Gomez, 1998).

Learning about a sequence in these paradigms can be acquired without intention to learn, although intentional learning produces qualitatively different effects (Jiménez et al., 2006). On the one hand, intentional learning appears to result in more flexible knowledge, which can be successfully transferred over some surface changes not involving a change in the sequential structure. For instance, intentional learners trained in the standard SRT task, in which a single stimulus is presented on each trial, can use their sequence knowledge to respond to a transfer block in which distractors are presented in the nontarget locations, thus requiring participants to discriminate target from distractors before responding to the target location. In contrast, incidental learning produces more specific knowledge, which can be applied over training with a single stimulus, but does not survive transfer to conditions requiring participants to discriminate targets from distractors. On the other hand, however, when the transfer conditions involve a decrease in the proportion of predictable trials, then incidental learners keep relying on their sequence knowledge, whereas intentional learners stop using it. For instance, when incidental learners trained with a continuously repeated sequence are transferred to a block in which only a few trials are consistent with that sequence, they keep responding faster to those few trials which still follow the training sequence. In contrast, when intentional learners are presented with the same conditions, they stop using their knowledge, so that the effect of learning is no longer observed over that transfer block. This pattern of results is consistent with the claim that only intentional participants become aware of the abrupt change in the proportion of predictable trials introduced over that transfer phase, and develop strategies oriented toward avoiding the use of knowledge that they experience as no longer valid. In contrast, incidental learners may simply be unable to notice such a change, and therefore they keep applying their knowledge regardless of the proportion of trials in which it is actually useful over a given block.

3. Conflict adaptation effects

The interpretation of these results in terms of the detection of a conflict between predicted and observed locations, and of the adoption of strategic adjustments in response to that conflict, resonates with a growing body of research concerning how the cognitive system deals with the competition arising on some tasks between the correct responses and some prepotent, but ultimately incorrect, response tendencies (Botvinick, 2007; Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick, Cohen, & Carter, 2004). This conflict has been investigated extensively using Eriksen's flanker tasks (Eriksen & Eriksen, 1974), Stroop tasks (Stroop, 1935) and Simon Tasks (Simon, 1969). In all these cases, conflict situations are built by asking participants to respond to one stimulus or stimulus' feature that is sometimes incongruent with another salient feature of the display. For instance, in the flanker paradigm participants may be told to respond to a central letter which is flanked by letters assigned to the opposite response, and in the Stroop paradigm participants are to name the color of the ink in which a word referring to a different color is written. In the Simon paradigm instead, participants are to respond to one stimulus' feature (e.g., color or shape) by pressing one of two keys (e.g., left or right) independently of the irrelevant left–right location of the stimulus. In all these cases, responding to a congruent trial (e.g., the red ink of the word "red") has been found to be faster than responding to an incongruent trial (i.e., the word "red" printed in blue), which is typically known as congruency effect. More important for the present purposes, it has also been shown that, despite the automatic and almost unavoidable nature of such congruency effects, the nature of the previous trial modulates the strength of the conflict, so that after congruent trials the congruency effect is larger than after incongruent trials (Gratton, Coles, & Donchin, 1992). The dependency of the congruency effect on previous congruency has been termed sequential congruency effects. The relative frequency of both congruent and incongruent trials has also been observed to affect the overall strength of the congruency effect (e.g., Lindsay & Jacoby, 1994).

Some authors have attempted to account for such effects in terms of the repetition of previous events (Hommel, Proctor, & Vu, 2004; Mayr, Awh, & Laurey, 2003). Thus, for example, on congruent trials preceded by congruent trials the exact stimulus and response can be presented (complete repetition), whereas on congruent trials preceded by incongruent trials some but not all features can repeat (partial repetition). As it is known that participants are faster in responding to complete than to partial repetitions, independently of congruency (Hommel, 2004), feature repetition priming might explain conflict adaptation effect. However, the sequential congruency effects have been found to survive even when the potential contributions from these episodic factors are taken into account (see Egner, 2007, for a review). Therefore, adaptation to conflict appears to be at least one of the factors accounting for these sequential congruency effects. Specifically, the conflict monitoring model put forward by Botvinick et al. (2001) and Botvinick et al. (2004) assumes that these effects depend on a running adjustment of control which is triggered by the detection of conflict over the previous trial. A dedicated system involving the dorsal anterior cingulate cortex (ACC) would register the conflict encountered over the last incongruent trial, and trigger the operation of prefrontal structures involved in increasing the control, thus decreasing the effect of congruency over the next trial. In contrast, a congruent trial will not be associated with any increase in control, and therefore will allow the activation of competing responses which hinder performance on successive incongruent trials.

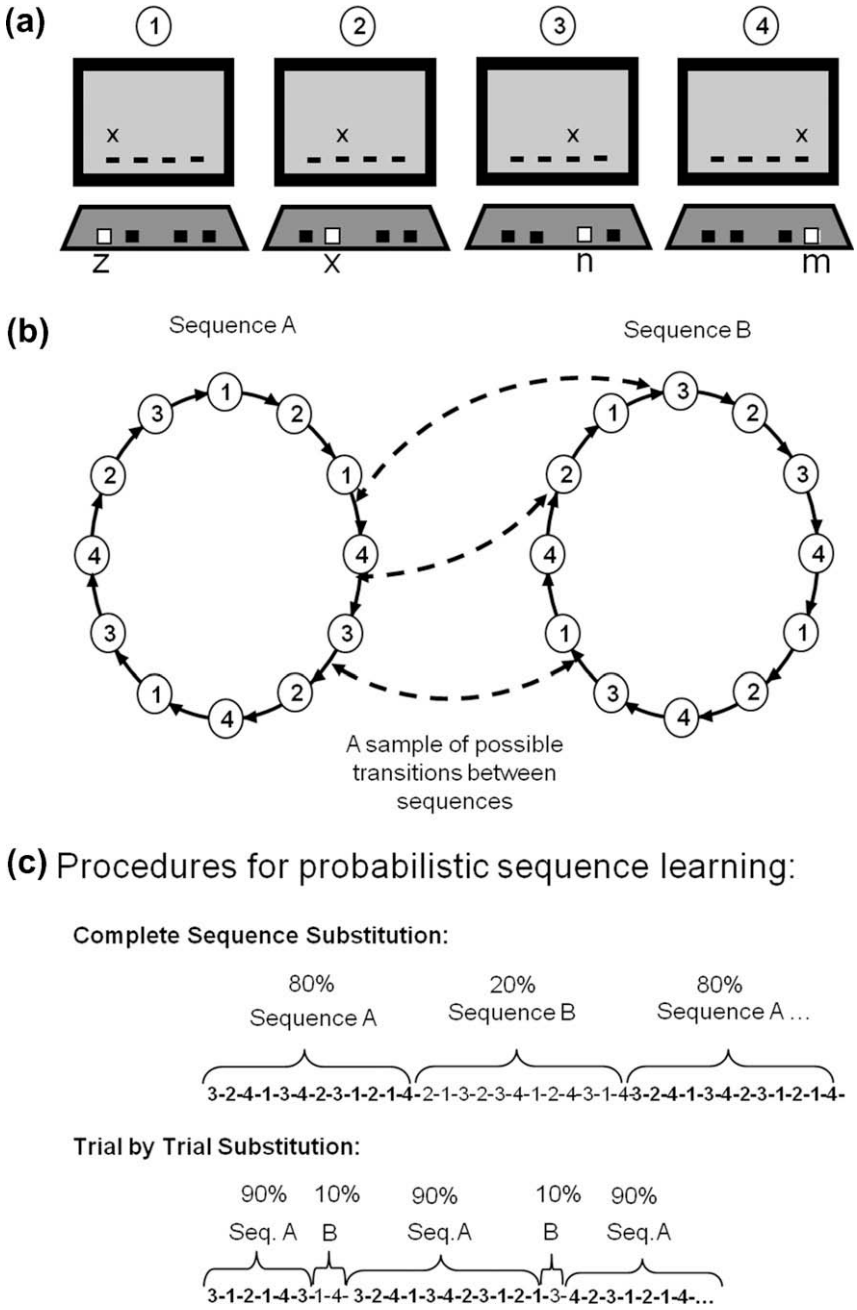

Fig. 1. Structure of a probabilistic sequence learning procedure. (a) Representation of the stimulus and the required key-presses for trial types 1, 2, 3, and 4, respectively. (b) Representation of the two 12-trial sequences used to generate either training or control trials for different participants (Sequence A and Sequence B). Both sequences are represented as recurrent structures to highlight that the sequences are continuously recycled, and that the starting point is randomly chosen on each block. A sample of possible transitions between sequences is also represented to illustrate that these transitions respect the second-order conditionals of the upcoming sequence. For instance, if a participant is trained with Sequence A and a control trial is scheduled to appear after the series 2–1–4, then the next trial would appear at location 2, which is the successor of the series 1–4 according to Sequence B. (c) Representation of the "complete sequence" and "trial by trial" substitution procedures employed in these probabilistic sequence learning tasks. In the former case, full series of 12 trials conforming to the control sequence are presented with a specific likelihood. In the latter case, individual trials obeying either the training or the control conditionals are interspersed with each other in a way that respects the transitions between trials as well as the overall likelihood of each type of trial (e.g., 90% of training vs. 10% of control trials). Notice that most trials obeying the unlikely control sequence would appear isolated, but small groups of control trials are also possible.

Egner (2007) has pointed out that such conflict monitoring model should be distinguished from related expectancy-based accounts (e.g., Gratton et al., 1992), and that none of them should be necessarily associated with a conscious mediation. Thus,

both the detection of a conflict on a given trial, and the development of a expectancy for the following trial could in principle be described as implicit effects (see Klapp (2007), Kunde (2003), Mayr (2004) for discussions about the conscious vs. unconscious nature of these effects).

4. Sequential congruency effects in sequence learning?

If conflict monitoring can operate implicitly, we contend that it should also work to modulate the expression of implicit learning effects. Perhaps the strongest test of this assumption will be to show sequential congruency effects in the expression of learned response tendencies of which participants are not even aware. Jiménez et al. (2006), Experiments 3 and 4 have shown that intentional learners can control for the expression of sequence learning whenever the training sequence becomes less valid over a full transfer block. In a similar vein, we may ask whether an analogous, but finer-grain control effect could be exerted implicitly to modulate the expression of sequence learning depending on whether the previous trials conformed either to the training sequence (i.e., congruent trials) or to a control sequence (i.e., incongruent trials). We will address this issue first by means of a reanalysis of some results reported in Jiménez et al., and then through a new experiment designed specifically to capture these sequential congruency effects on a trial by trial basis.

5. Reanalysis of Jiménez et al. (2006)

In Experiments 3 and 4 from Jiménez et al. (2006), we reported that only participants instructed to look for sequential contingencies (i.e., intentional learners) stopped using their sequence knowledge (i.e., they stopped being faster for sequence than for non-sequence trials) when the percentage of predictable sequence trials dropped abruptly over a transfer block, from 100% to just 12.5% (thus non-sequence trials being 87.5%). In contrast, incidental learners kept expressing their implicit sequence knowledge, as they were still faster on sequence than on non-sequence trials. However, it is worth noting that incidental learners in these two experiments also reacted about 25 ms slower to sequence trials presented over the transfer block than to the same type of trials when they were presented in the context of the immediately previous training block (100% sequential trials), $F(1, 39) = 10.20$, $\eta_p^2 = .21$, $p < .005$. Thus, even though incidental learners still used their knowledge over the transfer block to respond faster to training than to control trials, the former comparison suggests that the presence of conflicting stimuli over the transfer block may have affected responses to the sequential trials for incidental learners.

Experiments 1 and 2 from the same study allowed for a more systematic analysis of the effect of incongruent trials (i.e., non-sequence or control trials) over responding to the following trials, as participants in those experiments were continuously trained with noisy stimuli, which included trials conforming to both the training and the control sequence within each training block. In these probabilistic sequence learning conditions, a 12-trial training sequence was recycled continuously over 80% of the training trials, but this sequence was replaced by a control sequence of the same length for the remaining 20% of the trials. The series of locations were generated according to what we call a "complete sequence substitution procedure" (see Fig. 1, panel C) in which the 80/20 proportion was implemented by randomly intermixing eight series of 12 trials conforming to the training sequence with two series of 12 trials generated according to the complementary, control sequence. In Experiment 1 ($N = 32$), two incidental groups were trained over 12 training blocks. In Experiment 2 ($N = 56$) another incidental learning group was compared with a group of intentional learners, in which participants were presented with the same amount of training, but were informed about the existence of a regular sequence of locations that they could use to improve their performance. As a result of practice, participants in all groups learned to respond progressively faster to trials generated according to the most likely sequence than to those generated according to the control sequence.

In the following we will report a reanalysis of this set of data, in which we analyzed the implicit learning effect (i.e., the difference between responding to trained sequence and control trials), as a function of the type of trial encountered in the previous series. This way we will be able to investigate sequential effects on implicit sequence learning effects. Note that those experiments were not conceived for this goal. Therefore certain types of series successions were especially unlikely in this procedure. Indeed, the appearance of one series of 12 control sequence trials right after another control sequence series did never occur for 13 participants out of the whole sample of 88. In order to deal with this problem, reaction times (RTs) were averaged for each participant over the whole period of training. Fig. 2 represents the average RT produced in each of the four conditions: responses to series of 12 trials of either control or training sequences, in terms of the type of trials (training or control sequence) presented in the immediately preceding 12-trial series.

A mixed-model ANOVA conducted over the mean RTs, using Group (4) as a between-participants factor, and both Sequence (Training vs. Control) and Previous Sequence (Training vs. Control) as within-participants factors, confirmed that responding to training trials was significantly faster than responding to control trials, $F(1, 71) = 81.94$, $\eta_p^2 = .54$, $p < .0001$. More important for the present purposes, the analysis also showed a significant Previous Sequence $\times$ Sequence interaction $F(1, 71) = 11.62$, $\eta_p^2 = .14$, $p < .005$. As it can be observed from Fig. 2, responding to control sequence trials was uniformly slow regardless of the status of the previous series ($F < 1$). In contrast, responding to training sequence trials was significantly slower after control sequence trials than after training sequence trials, $F(1, 84) = 60.26$, $\eta_p^2 = .42$, $p < .0001$. This latter result was quite consistent across groups (no relevant interaction involving Group approached significance), and crucially, it was observed in both intentional and incidental learners. We surmise that the effect captured by this reanalysis is different from the absolute disappearance of sequence learning effects that was exclusively observed for intentional learners in Experi-

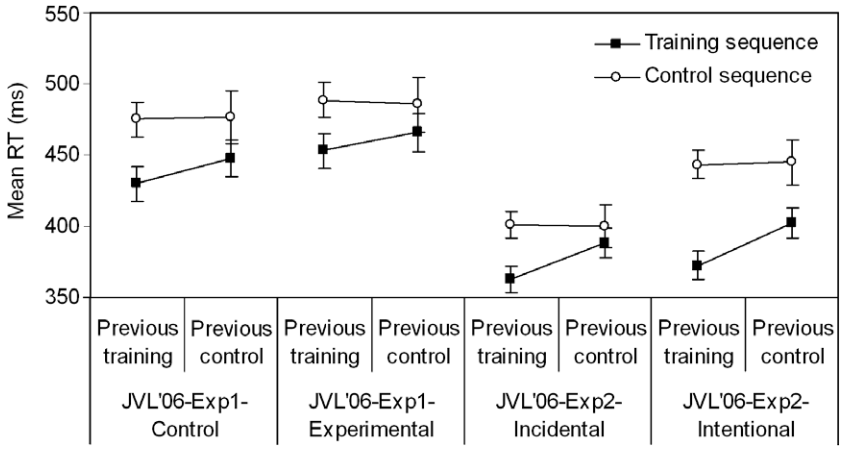

Fig. 2. Mean RT for Training and Control sequences from four different conditions of Jiménez et al. (2006), represented as a function of whether the preceding sequence was a training or a control sequence. Error bars represent standard errors of the mean.

ments 3 and 4 from the same study (Jiménez et al., 2006). Whereas in these two experiments the effect may reflect a strategic decision to stop using the acquired knowledge after having experienced that it is no longer useful over a full block, it appears that the effect captured through the above reanalysis might reflect a more automatic modulation of the effect of sequence learning, which would depend more directly on the effect that the conflict encountered over the last few trials could produce on the control of the expression of learning over the following trials.

One may wonder, however, whether the effects captured by this reanalysis could still be interpreted as the product of a strategic decision taken by the participants after noticing that a full series of 12 trials failed to fulfill the learned expectancies. Indeed, arranging complete series of 12 training or control trials may provide learners with enough opportunities to detect global changes, and perhaps to adopt rapid, but strategic, decisions depending on the usefulness of their learned expectancies as perceived over the last few trials. In contrast, if such conflict effects may arise even after a single deviant trial (i.e., one trial not conforming the trained sequence), and if they appear equally for incidental and intentional learners, this could resemble much more like the sequential congruency effects which are often observed in other conflict tasks, and which have been interpreted in terms of the operation of automatic processes of control. Providing such evidence was the goal of the current experiment.

6. Trial-by-trial modulation of implicit sequence learning

6.1. Method

To ascertain whether the expression of sequence learning can be modulated by the sequential status of a single previous trial, we designed an experiment which followed the trial-by-trial substitution procedure first developed by Schvaneveldt and Gomez (1998). Thus, instead of replacing complete series of 12 training trials with a control series of the same length, the trial-by-trial procedure generated each trial according to either the training sequence in 90% of the trials, and according to the control sequence in the remaining 10% of trials, on an individual basis. By having a continuous chance of replacing the successor prescribed by the training sequence with that marked by a complementary, control sequence, this procedure made it difficult for participants to break through the regular structure. Moreover, by choosing training trials much more often than control trials (relative proportions of .90 vs. .10) this procedure allowed implicit learning effects to accrue gradually with training. In these conditions, we surmise that explicit learning effects would be difficult to arise, because overt expectancies would always be contradicted on a number of trials. Thus, we expected to find only minimal differences between intentional and incidental learners. However, to get a direct measure of how the acquired knowledge could be explicitly used by participants to predict the more likely successor of each fragment, we arranged a cued generation task by the end of training.

We will analyze the implicit learning effect as a function of the nature of the immediately preceding trial. We expect the expression of implicit learning to be reduced after control trials (as compared to the effect observed after training trials). To the extent that this modulatory effect is implicit we expect it to be similarly observed in the intentional and the incidental learning groups.

6.1.1. Participants

Forty one students from the University of Granada took part in this experiment in exchange for course credits. They had never participated in similar experiments before. Participants were randomly assigned to two groups receiving either intentional or incidental instructions. Intentional participants were informed about the existence of a regular sequence of loca-

tions that was going to be respected in most, but not all trials, and they were urged to try to discover this regularity, and to use it as a way to improve their performance. All participants were also instructed to respond to the location of each trial as fast and accurately as possible, but they were told that their data could not be considered if they produced errors in more than 10% of the trials. Data from two participants who did not reach this criterion were discarded. Thus, the analyses were conducted on 20 incidental and 19 intentional participants.

6.1.2. Apparatus and materials

The sequence of stimuli was generated by a personal computer, and presented on a 14-in. screen. The program that controlled the experiment was written on E-Prime (Schneider, Eschman, & Zuccolotto, 2002) software. Participants' responses were entered through the keyboard.

6.1.3. Procedure

An X was presented on each trial at one of four locations distributed over the horizontal axis of a computer screen. Four horizontal short lines marked the locations at which the imperative stimulus could appear. Participants were told to respond to the location of the stimulus, from left to right, using the middle and index fingers from both hands to respond on spatially corresponding keys (Z, X, N, and M, respectively). The next trial appeared 200 ms after any response, regardless of the accuracy of the response. In case of error, however, visual feedback was presented over the response-to-stimulus interval. Referring to each location, from left to right, with the digits 1–4, two sequences were used: 121432413423 and 323412431421. One was used as training and the other as control sequence (see Fig. 1, panel B, for a representation of these sequences). Notice that these two sequences are structurally analogous, so that one is created from the other by replacing locations 1 and 3. They both contain all possible transitions, with the exception of repetitions, which are forbidden. They can be taken as second-order conditional structures in that after any single location all the remaining three locations are equally probably, but any series of two consecutive locations does completely determine the legal third successor of the series (Reed & Johnson, 1994). The two sequences are also maximally discriminative, in that the successor of any series of two consecutive locations is always different between the two sequences (for instance, after the series 21 the legal successor is 4 in Sequence A, but 3 in Sequence B). These sequences were randomly assigned as training or control sequence for each individual learner.

Participants were trained over nine blocks of 120 trials. Each block started randomly by selecting the first two trials at chance without repetition. From here on, the program proceeded selecting the successor of these two trials according to either the training sequence (in 90% of the trials), or the control sequence (in 10% of the trials). So, for instance, if Sequence A was chosen as the training sequence for a given participant, and locations 2–1 had been randomly sampled over the first two trials, then the third trial would appear at location 4 with a probability of .9, and at location 3 with a probability of .1 (see Fig. 1, panel B). From here on, the same logic applied iteratively to generate the fourth and successive trials depending on the context established by the two immediately previous trials.

After nine training blocks, two transfer blocks were arranged in which these probabilities were shifted from .90/.10 to .20/.80, so as to test whether the acquired sequence knowledge would still be applied in conditions in which it was no longer a valid predictor of the next location. Using these probabilities over transfer allowed us to assess the expression of sequence learning over a sufficient amount of predictable trials (20% of the trials over two blocks), while maintaining a pattern in which it would be more advisable to avoid being affected by such knowledge. We expected that, if this sequence knowledge has become explicit, then participants would notice that the learned sequence was no longer applicable, and hence they would adopt a strategic decision against using it (Jiménez et al., 2006). In contrast, if the effects of learning continued to affect performance over these transfer blocks, this could be interpreted as consistent with the claim that participants failed to notice the change introduced over this phase, arguably because their learning remained implicit. After this transfer phase, the training probabilities were restored over a final training block, as a way to re-establish the learned contingencies before proceeding to measure sequence knowledge through a direct measure of performance.

In this cued generation task, we assessed participants' ability to make direct predictions in response to a fragment of the sequence. Each test started with a cue composed by a two-trial fragment to which participants responded as in the standard SRT task, followed by a third trial in which they had to generate the most likely successor of that fragment. Thus, for instance, after responding to the fragment 2-1, participants were presented with a display containing question marks on the locations 3 and 4 (i.e., the alternative successors of that fragment as prescribed by each of the two sequences), and they were asked to choose which of these two successors was more likely to have followed that fragment over the whole experiment. Each of the 12 possible fragments of two trials was presented twice, in random order, thus completing a full set of 24 generation tests.

Indirect measures of sequence learning were taken from training blocks 1–9, by comparing the average RT over these blocks in response to either training or control trials. Participants' ability to strategically control the deployment of their sequence knowledge was assessed over the transfer blocks (10 and 11), by analyzing whether they kept responding faster to those trials generated according to the training sequence even over those blocks in which most of the trials followed the control sequence. Direct measures of sequence knowledge were taken from performance on the cued generation task, by assessing whether participants generated more often the training than the control successors of all relevant fragments. Finally, and most important for the current purposes, the sequential congruency effects were assessed over the training blocks (1–9), by examining whether the effects of sequence learning (i.e., the difference between responding to training and control trials) were modulated by the sequence status of the preceding trial.

7. Results and discussion

7.1. Indirect measures of sequence learning

The first two trials from each block, as well as error responses (4.3% of the trials), and outliers, defined as those trials departing more than three standard deviations from the specific mean from each participant and block (1.6%), were eliminated from the analyses. Mean RT for trials corresponding to training or control sequences were computed separately for each block. Learning was analyzed through a mixed-design ANOVA on these mean RTs, with Task Orientation (2) as a between-participants factor, and with both Training Block (9) and Trial Type (2) as repeated factors. For the effects and interactions involving Training Block, we report nominal degrees of freedom along with Greenhouse-Geisser ε and adjusted p-levels.

The ANOVA confirmed significant main effects of Trial Block, $F(8, 296) = 3.14$, $\eta_p^2 = .08$, $p < .01$, $\varepsilon = .69$, and Trial Type, $F(1, 37) = 62.85$, $\eta_p^2 = .63$, $p < .0001$, as well as a significant Trial Block × Trial Type interaction, $F(8, 296) = 4.02$, $\eta_p^2 = .10$, $p < .001$, $\varepsilon = .76$. No effect or interaction involving Task Orientation reached significance in this analysis. As shown in Fig. 3, these results indicate that training produced a similar improvement in both groups, that RTs were generally faster from training than for control trials, and that the difference between training and control trials grew steadily with practice. A linear contrast confirmed this impression by showing a significant linear trend for the Trial Block × Trial Type interaction, $F(1, 37) = 20.29$, $\eta_p^2 = .35$, $p < .0001$.

The response tendencies acquired over training appeared to be roughly maintained over the transfer blocks. Thus, although the first transfer block produced a strong impact in performance, participants in both conditions kept responding faster to training than to control trials. A Mixed ANOVA conducted on RT over these transfer blocks, with Transfer Block (2) and Type of Trial (2) as within-participants factors, and Task Orientation as a between-participants variable, showed that performance improved between the first and the second transfer block, $F(1, 37) = 10.1$, $\eta_p^2 = .22$, $p = .005$, but that the effect of Type of Trial was maintained over these two blocks, $F(1, 37) = 21.22$, $\eta_p^2 = .36$, $p = .0001$. No other effects or interactions approached significance.

7.2. Sequential congruency

Because of the reduced number of cases in which a control trial was preceded by another control trial, we collapsed all training blocks to analyze the effects of sequential congruency. In compliance with a common practice in the literature, for this analysis we also excluded post-error trials, which are typically associated with increased RTs (Rabbitt, 1966). An ANOVA on RT with Task Orientation (2) as a between-participants variable, and Trial Type (2) and Preceding Trial Type (2) as within-participants factors, showed a significant effect of Trial type, $F(1, 37) = 10.79$, $\eta_p^2 = .23$, $p < .01$, and a significant Trial type × Preceding Trial Type interaction $F(1, 37) = 12.79$, $\eta_p^2 = .26$, $p = .001$, independently of Orientation (Fs < 1 for all effects and interactions involving group). As shown in Fig. 4, and confirmed through follow-up analyses, the observed interaction

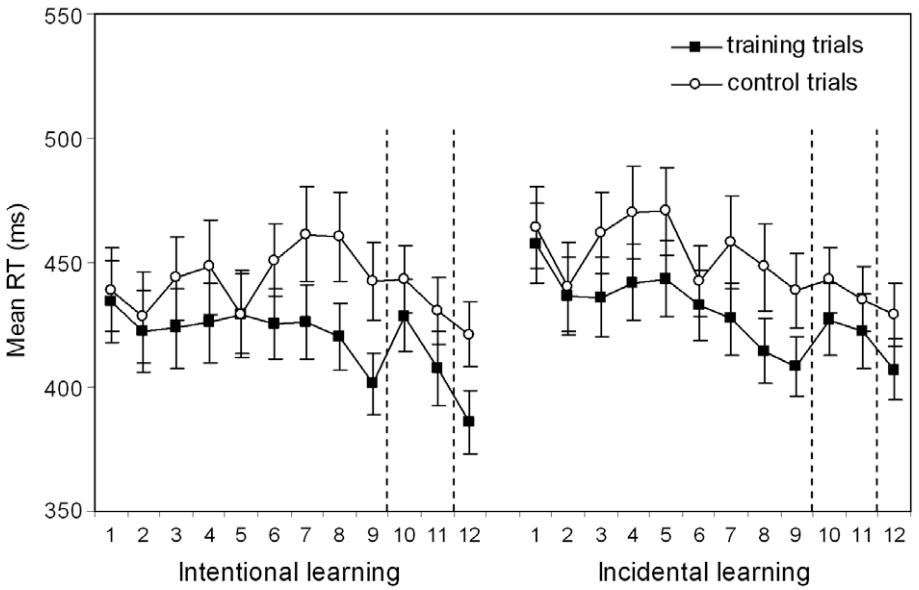

Fig. 3. Mean RT for Training and Control trials represented across training (blocks 1–9 and 12) and transfer blocks (blocks 10–11), separately for intentional and incidental learning conditions. Error bars represent standard errors of the mean.

reflected the existence of a strong effect of Trial Type when the preceding trial followed the training sequence, $F(1, 37) = 87.15$, $\eta_p^2 = .70$, $p < .0001$, which disappeared completely when the preceding trial was a control trial ($F < 1$). Plainly then, it appears that including a single control trial within a series of sequential trials produces a momentarily switch in participants' reliance on their sequence knowledge, just as it could be expected if participants' experience of a conflict between predicted and observed locations could trigger an increase in the control exerted over the following trial. Crucially, this effect was not mediated by the incidental vs. intentional orientation of the learners.

7.3. Direct measures of learning

According to the hypothesis that sequence learning in these probabilistic training conditions could remain largely implicit, generation performance did not show that participants were particularly efficient at discriminating between training and control successors of each fragment when they were directly asked to do so. The average proportion of generation of the training successors was significantly larger than that expected by chance, .56, $t(38) = 3.76$, $p < .001$. Although in absolute terms intentional learners outperformed incidentals (.59 vs. .54), such difference turned out not to be statistically significant, $F(1, 37) = 1.99$, $p = .17$. Note that generation performance could be sensitive to implicit knowledge as well, and after all the general pattern of results showed only a modest ability to discriminate between training and control successors of each series. Furthermore, no beneficial effects from instructions were observed, whereas such learning orientation effects have been found in previous studies using deterministic sequences over training, e.g. Jiménez et al. (2006). All these factors can be taken as evidence indicating that learning proceeded in an implicit way in both incidental and intentional learning conditions.

To further reinforce the claim that both the effects of sequence learning and those of sequential congruency could be nonconscious, we rerun these analyses after removing, for each learner, those RTs corresponding to the parts of the training sequence which had been correctly generated in response to the appropriate cues. Thus, for instance, if a participant trained with Sequence A generated location 4 the two times in which he or she was prompted with the fragment 21?, then RTs corresponding to that part of the sequence were removed from the data for this particular learner. The pattern of results was not substantially changed by this restriction. The corresponding ANOVA for the effect of sequence learning over those trials which were not generated better than chance still showed significant main effects of Trial Block, $F(8, 296) = 2.97$, $\eta_p^2 = .07$, $p < .05$, $\varepsilon = .69$, and Trial Type, $F(1, 37) = 28.08$, $\eta_p^2 = .42$, $p < .0001$, as well as a significant Trial Block × Trial Type interaction, $F(8, 296) = 3.19$, $\eta_p^2 = .08$, $p < .01$, $\varepsilon = .78$. As for the sequential congruency effect, the analyses conducted on those training trials which had not been generated better than chance also showed a significant effect of Trial Type, $F(1, 37) = 4.54$, $\eta_p^2 = .11$, $p < .05$, and a significant Trial type × Preceding Trial Type interaction, $F(1, 37) = 10.65$, $\eta_p^2 = .22$, $p = .01$.

8. General discussion

To test the assumption that sequential congruency effects could be observed for tendencies of which participants are not even aware, we assessed whether congruency effects could be obtained over an implicit sequence learning paradigm.

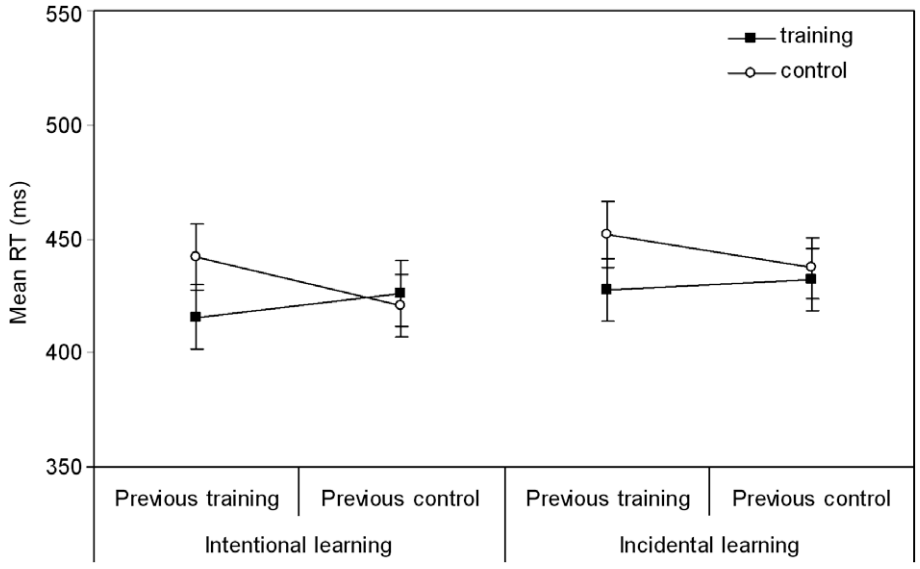

Fig. 4. Mean RT for Training and Control trials as a function of the type of trial presented on the preceding trial ($N - 1$), and separately for intentional and incidental learning conditions. Error bars represent standard errors of the mean.

According to this hypothesis, the effects of a learned sequence should be larger after a group of trials which conforms to the training sequence than after a comparable group of trials (or even a single trial) which fails to comply with that structure. A reanalysis of previous results reported in Jiménez et al. (2006) provided strong support for the idea that the effects of sequence learning are modulated by the sequential status of the previous trials. Moreover, the results from a new experiment in which training and control trials were intermixed with each other on an individual basis also showed that the expression of sequence learning was strongly affected by the status of the previous trial, in much the same way as the congruency of the immediately previous trial has been shown to modulate the congruency effect over the following trial in Stroop, Simon or flanker tasks.

8.1. Implicit nature of sequential congruency effects

We contend that the sequential congruency effects reported in this study are implicit because they are equivalent for intentional and incidental learners, because they arose in a probabilistic version of the sequence learning paradigm which is known to minimize the acquisition of explicit knowledge (Jiménez & Vázquez, 2005), and because they are found even for sequence trials which were not generated better than chance. Even though participants did generate the appropriate successors of the relevant contexts slightly better than chance, the measure of generation did not distinguish between intentional and incidental learners, and thus it might be taken to reflect a blend between implicit and explicit effects. Moreover, the fact that participants in both intentional and incidental conditions kept relying on the training sequence even upon a transfer phase in which most of the trials appeared at different locations than those predicted by the training sequence does strongly indicate that such knowledge was not being strategically applied (cf. Jiménez et al., 2006).

Thus, the overall pattern of results is much more compatible with the action of an automatic process of conflict monitoring than with the controlled effect of an overt expectancy. A possible account for these results could argue that, as participants get progressively used to respond to a sequence, they might notice the conflict produced over a control trial, even if they do not become aware of the specific details underlying the sequence. Noticing the conflict on a given trial could automatically foster a more cautious response on the following trial and thus affect the expression of implicit learning.

This account is analogous to the way in which the conflict monitoring model (e.g., Botvinick et al., 2001, 2004) has accounted for conflict adaptation effects in other conflict tasks, such as Stroop, Simon or flanker tasks. Importantly, however, these results demonstrate that the process of conflict detection can take place even when the conflicting response tendencies remain largely implicit.

At variance with the processes involved in other conflict tasks, the control processes involved in sequence learning tasks do not imply micro-adjustments in the processing of task-irrelevant dimensions of a single stimulus, but rather in the processing of a more global dimension which characterized the full set of stimuli, as it is its underlying sequence. Just as in a Stroop task the meaning of a word cannot be completely ignored when responding to the color in which it is printed, we surmise that the sequence of locations in an SRT task cannot be filtered out even though the task requires only to respond to each individual location. Thus participants learned automatically about the training sequence, and the expression of this learning gets automatically modulated by the conflict perceived on the previous trial between these learned tendencies and the specific response required on that trial.

8.2. Alternative accounts

Alternative accounts proposed for the standard sequential congruency effects, such as those built in terms of episodic factors (Hommel et al., 2004; Mayr et al., 2003), should also be considered with respect to the effects reported in this study. For instance, an episodic argument could be raised to account for the effects revealed in the reanalysis of Jiménez et al. (2006), in which entire series of training and control trials were intermixed with each other. In these conditions, responding to a repeated training sequence could provide an advantage with respect to responding to the same sequence after a control series, because the immediate repetition of a series could lead to a short-term advantage in performance. However, an ANOVA conducted over the first two blocks from these experiments, just before sequence learning was acquired, did not sustain this claim. Rather, this analysis showed no significant interaction between type of sequence and the preceding type of sequence ($F < 1$), and thus no hint for an advantage of series repetition independent of sequence learning (i.e., before it takes place). Plainly, it appears that if repetition effects could exist in this paradigm, they do not survive a whole series of 12 trials.

Moreover, episodic accounts have even more difficulties to account for the results of the experiment reported in this study, in which training or control trials were administered individually. In this case, the trial by trial substitution algorithm provoked that, on the average, the number of trials intervening between two repetitions of a training fragment becomes shorter after a control trial than after a comparable series of training trials. Indeed, when the training sequence was not disrupted, training triplets (i.e., series of three locations) recurred only after a full series of 12 trials. In contrast, including a control trial did usually provoke a restarting of the training sequence at a different point, depending on the context made up by the preceding trial plus the upcoming control trial. This restarting process did actually increase the probability of repeating a recently observed triplet short after a control trial. Therefore, if repetition effects played a role in these conditions, one should expect responses to training trials to be faster after a control trial than after a larger series of training trials. This is exactly opposite to the observed effect: the removal of the expression of sequence learning after a control trial. Thus, one must conclude that episodic repetition effects cannot account for the observed modulation of learning.

Finally, even conceding that the observed difference in responding to training trials in terms of the status of the previous trial is a product of learning, one may take issue with whether such effects are caused by a cognitive conflict provoked by presenting an incongruent trial, or simply by the distortion introduced in the sequence by that control trial, which precludes the use of larger-order conditional information (runs or long fragments). Such an argument can hardly be applied to the conditions in which full training and control series were arranged (i.e., the data from Jiménez et al., 2006), because in this case the disruption of larger-order information is minimal (i.e., it could only affect to the very first trials of a series). However, the argument can be raised as a valid alternative to account for the results obtained with the trial-by-trial substitution procedure. In this case, indeed, a training trial which occurs right after a control trial (e.g., 21**3**4, where Sequence A acts as the training sequence, 3 is a control trial, and 4 is the successor of this series according to the training sequence, see Fig. 1) is defined as consistent with the training sequence because it implements the appropriate successor of the two previous trials according to the relevant sequence (in this case, 134 is a consistent fragment). However, it is necessarily inconsistent with the sequence as judging form larger-order conditional dependencies, because that larger context contains at least one incongruent transition (i.e., the one leading to the control trial). In contrast, training trials occurring right after another training trial often follow a large number of other training trials, and thus could be benefited from learning about larger-order conditional information. This bias is unavoidable in this kind of design, but it could be minimized by assessing the impact of the status of the preceding trial ($N-1$) on the effect of learning manifested on a given trial N, conditioned to cases in which the status of the last-to-previous trial ($N-2$) was different from that of $N-1$. In this way, we could assess the effect of a single training or control trial over the effect of sequence learning as expressed on the following trial (i.e., the effect of $\text{control}_{(n-1);\ \text{training}\ (n-2))}$ vs. $\text{training}_{(n-1);\ \text{control}\ (n-2))}$ on the learning observed on the $\text{current}_{(n)}$ trial). The pattern of results got basically replicated in this analysis, again showing a significant effect of Trial Type, $F(1, 37) = 13.74$, $\eta_p^2 = .27$, $p < .001$, and a significant interaction Trial Type × Preceding Trial Type, $F(1, 37) = 14.02$, $\eta_p^2 = .27$, $p < .001$. The results still showed a clear effect of sequence learning after a single training trial, $F(1, 37) = 40.26$, $\eta_p^2 = .52$, $p < .0001$, but no effect of learning after a single control trial ($F < 1$).[1]

The results just described are therefore conclusive in showing that the expression of sequence learning relies heavily on whether the previous trial was consistent or not with the implicitly learned sequence. A potential account for this effect can be built in terms of the influential conflict monitoring model put forward by Botvinick and his coworkers (Botvinick, 2007; Botvinick et al., 2004), which endows the ACC with the functions of assessing the conflict on each trial, and of recruiting other prefrontal structures whenever it becomes necessary to overcome such conflict. This account is consistent with the results of neuroimaging studies of sequence learning which have found an increase in the activation of ACC when a sequence is conscious (Aizenstein et al., 2004; Destrebecqz et al., 2005), but also when participants are presented with a non-conscious change between two probabilistic sequences (Berns, Cohen, & Mintun, 1997). Thus, it appears that the conflict monitoring system could become activated automatically in response to any conflict signal, and that the increased control provoked by the eventual recruitment of prefrontal structures could help learners to reduce the conflict on the following trials.

As a final note, it is important to notice that the pattern observed over the transfer blocks from the present experiment is not consistent either with a modulation of these control processes on the basis of conscious expectancies, or with the predictions of a static process of conflict monitoring. On the one hand, if participants were able to consciously detect the decrease in the proportion of predictable trials produced between training and transfer phases (from 90% to 20%), then they should be expected to adopt a strategic decision to stop relying on their knowledge over the transfer blocks, and thus to show no effect of sequence learning over these blocks. On the other hand, if they were completely insensitive to the changes introduced at transfer, then they should be expected to keep showing the same sequential congruency effects over these transfer blocks as they showed over the previous training blocks. However, given that over these transfer blocks 80% of the trials were control trials, then most of the training trials should have occurred right after a control trial, and thus should have resulted in a dramatic decrease of the effect of learning. In contrast to both predictions, the survival of the expression of sequence learning over these transfer blocks points simultaneously to two important conclusions: (a) that the learners were not becoming aware of the fact that the training sequence was no longer informative over this transfer phase and (b) that, in spite of this lack of awareness, the unpredictable trials affected less strongly to the expression of sequence learning when they become more likely over these transfer blocks. This effect resembles the proportion congruency effect which has been reported in other conflict tasks (e.g., Cheesman & Merikle, 1986; Lindsay & Jacoby, 1994), only that in the present study it has been found under conditions in which the source of congruency was learned, and in which both this learning, and the manipulation of the proportion of congruency, remained implicit. Thus, it appears that implicit regulation of implicit cognition is not only possible, but it could be at least as finely modulated by the context as are some of our more sophisticated and explicit beliefs.

[1] In response to a suggestion from an anonymous reviewer, we assessed the role that negative priming might have played in the production of these sequential congruency effects. Indeed, negative priming was a potential issue in 5 out of the 12 possible transitions between sequences in which, after replacing a training trial with a control trial, the context formed by doing so required the next trial to appear precisely at the allegedly inhibited location. For instance, according to Sequence A, after the series 21 location 4 should follow (see Fig. 1, panel B). In this context, however, a control trial could appear at location 3, thus forming a new context (13) in which the legal successor according to the training sequence would again be the "inhibited" location 4. To assess the impact of this potential problem we rerun the relevant Trial Type × Preceding Trial Type ANOVA after removing all those training trials which incur in those circumstances. The relevant Trial Type × Preceding Trial Type interaction was not changed by this restriction, $F(1, 37) = 20.74$, $\eta_p^2 = .36$, $p < .0001$.

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