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Luis Jiménez [a]; Gustavo A. Vázquez [a]
[a] Universidad de Santiago, Spain

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Implicit sequence learning in a search task

Luis Jiménez and Gustavo A. Vázquez
Universidad de Santiago, Santiago de Compostela, Spain

This study investigated the effects of selection demands on implicit sequence learning. Participants in a search condition looked for a target among seven distractors and responded on the target identity. The responses followed a deterministic sequence, and sequence learning was compared to that found in two control conditions in which the targets were presented alone, either at a central location or over a series of unpredictable locations. Sequence learning was obtained in all conditions, and it was equivalent for the two variable location conditions, regardless of the perceptual demands. Larger effects of learning were observed in the central location, both on the indirect measures and on the measures taken from a cued-generation task. The expression of learning decreased selectively in this condition when the sequence validity was reduced over a test block. These results are consistent with the claims that implicit and explicit learning are mixed in this central condition and that implicit learning is not affected by selection difficulty.

Keywords: Attention; Implicit learning; Perceptual load; Selective attention; Sequence learning; Serial reaction time task.

Many everyday skills can be taken to rely on implicit sequence learning, in that learning arises unintentionally, and it produces effects that go beyond the learners' ability to report on their knowledge. This learning has been modelled through the serial reaction time (SRT) task, in which participants are required to respond to a series of stimuli that follow a hidden sequence (Nissen & Bullemer, 1987). This task constitutes a simplification of most natural sequence-learning situations in that the stimulus appears alone at a reduced number of locations, and it remains on the screen until a valid response is produced. Recent studies have suggested that some of these details might not be as irrelevant as initially considered. For instance, requiring participants to perform a continuous-tracking task has been shown to decrease learning as compared to that found when participants respond to discrete stimuli (Chambaron, Ginhac, Ferrel-Chapus, & Perruchet, 2006). In a similar way, we aim to investigate whether learning about a sequence of stimuli appearing as a part of a complex scene can be different from responding to single targets.

Selection difficulty has been studied in the context of the SRT task as part of an overall discussion on the role of attention in sequence learning (e.g., Rowland & Shanks, 2006; Shanks,

Correspondence should be addressed to L. Jiménez, Facultad de Psicología, Universidad de Santiago, Campus Universitario Sur, Santiago de Compostela, E-15782, Spain. E-mail: jimenez@usc.es

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2003). As the authors pointed out, looking at whether sequence learning is affected by increasing perceptual demands can inform us not only about the degree in which sequence learning can be generalized to complex ecological settings, but also about the theoretically important question of whether it depends on the resources devoted to cope with these perceptual demands.

The role of attention in implicit learning has been the object of a lively debate focused around the notions of attention as a pool of resources and as a filtering process that selects for the relevant inputs and against irrelevant dimensions (Jiménez, 2003; Shanks, 2003). The notion of attention as a pool of resources was approached by exploring whether implicit sequence learning was affected by interposing a concurrent task. The first studies that followed this strategy suggested that implicit sequence learning depended on the integrity of attentional resources, as was inferred by performing a secondary task (Nissen & Bullemer, 1987). However, subsequent studies qualified this conclusion by showing that distraction could interfere with the expression rather than with the acquisition of learning (Frensch, Lin, & Buchner, 1998; but see Shanks, 2003) and that even in cases in which an acquisition deficit arose, this could be attributed to an interference on *explicit* effects (Jiménez & Méndez, 1999; Jiménez & Vázquez, 2005), or to an integration between the sequential stimuli and the random stimuli presented in the context of the secondary task (Jiménez & Vázquez, 2005; Schmidtke & Heuer, 1997).

As for the effect of attention as a filtering process, most researchers assume that participants can selectively learn only about those dimensions they attend to, but the problem arises on how efficient these filtering processes could be. In a task requiring responding to the stimulus locations, Jiménez and Méndez (1999) showed that participants learned about the shapes of these stimuli only when they were led to consider those shapes in the context of a secondary task. Other authors, however, have found that learning about a series of irrelevant locations can be produced when participants respond to another stimulus dimension (Mayr, 1996), at least if the response dimension is also sequentially structured (Deroost & Soetens, 2006). These results are consistent with the view that selection is not an all-or-none phenomenon, but that it varies in efficiency depending on complex factors that need to be further studied.

Lavie (2005) has recently pointed out that these two meanings of attention might not be independent, in that the efficiency of a selective process might be affected by task demands. If selection is taken to require specific resources, then the manipulations of selection difficulty could be informative not only with respect to the processing of nonselected stimuli, but also with respect to whether sequence learning depends on these specific resources.

Rowland and Shanks (2006) designed a series of experiments in which one or two distractors appeared with the target, resulting in a "filtering cost" that was inferred through the production of slower reaction times (RTs). Despite such increase in perceptual demands, no impairement was observed in learning, suggesting that "implicit sequence learning is resistant to disruption of the selection process" (p. 287). However, Rowland and Shanks concluded that their selection task might have not been sufficiently demanding and argued that more demanding tasks could yield different results. Starting from this argument, we aimed at increasing this selection difficulty, embedding the SRT task within a search task in which participants looked for a target among seven distractors and responded on the identity of this target.

Method

Participants were presented with eight digits distributed pseudorandomly over 16 possible locations arranged on an invisible 4×4 matrix. The targets followed a sequence that learners could exploit to improve performance. We compared sequence learning under this perceptually demanding task with two different control conditions in which the perceptual load was lower. In a first control group perceptual load was decreased by removing the distractors, but the target appeared at the same variable locations, in order to analyse whether the spatial uncertainty could produce any effect independent from perceptual load. In the second control group, we removed both factors by presenting the targets alone at the centre of the screen. Because the search conditions were expected to hinder the acquisition of explicit learning, we arranged a deterministic sequence, rather than the probabilistic procedure devised by Rowland and Shanks (2006). Additionally, because recent evidence has shown that contextual changes can affect differentially implicit and explicit learning (Jiménez, Vaquero, & Lupiáñez, 2006), we decided to avoid introducing contextual changes between training and test phases and thus tested sequence learning under the same conditions in which it was acquired. This decision might have been problematic if the effects of learning were negatively affected by perceptual load, because the difference could have been attributed to a deficit in either the acquisition or the expression of learning. However, because the previous evidence had shown effects of contextual changes, but not effects of input load, we considered it safer to avoid introducing such changes between training and test phases.

To test for the expected differences in explicit knowledge between groups, we included a cued generation task, and we also devised an indirect way of assessing the effects of explicit knowledge over the test block. Explicit learning has been shown to be specifically affected by changes in the sequence validity (Jiménez et al., 2006), arguably because explicit learners can notice the validity change and subsequently adapt their performance to their new expectations. To analyse this effect, our test block contained both sequential and control trials, so that we could assess whether the effects of learning were reduced when assessed within a low-validity block.

Participants

A total of 90 students participated in the experiment in exchange of a 5€ incentive. A total of 30 participants were assigned to each condition: central, variable location, and search.

Apparatus and display

The experiment was run on Pentium III PCs connected to colour monitors. Responses were made on Spanish QWERTY keyboards. The experimental program was designed on INQUISIT 1.31.

The stimuli consisted of a set of coloured digits printed in Garamond font, 1.1 cm high × 0.7 cm wide, over a grey background. Target stimuli were even numbers (2, 4, 6, 8) presented in random colours (red, blue, green, or yellow). In the central condition the target was presented alone at the centre of the screen. In the search condition the target appeared on each trial at one of the 16 locations defined by an invisible 4 × 4 matrix, 8.4 cm wide × 8.6 cm high, accompanied by seven distractors. Vertical and horizontal lines divided the matrix into four quadrants. Between neighbouring slots there was a horizontal separation of 1.9 cm and a vertical separation of 1.4 cm. The location of the target was decided pseudorandomly on each trial, with the only constraint that all 16 possible locations should be sampled before any of them was repeated. The distractors were seven instances of the same odd number, randomly chosen for each trial from the set 1, 3, 5, 7. The seven distractors plus the target stimulus were coloured and located pseudorandomly, so that two of them were drawn in each possible colour (red, blue, green, and yellow), and two items were located at each one of the matrix quadrants.[1] Finally, in the variable location condition the locations of the target followed the same constraints as those described for the search condition, except that the distractors were removed (see Figure 1).

[1] Some of these details were designed to enable us to adapt the paradigm to produce contextual cueing effects (Jiang & Chun, 2001) in forthcoming experiments. In this experiment, however, the distractors were arranged so as not to convey any information about the targets.

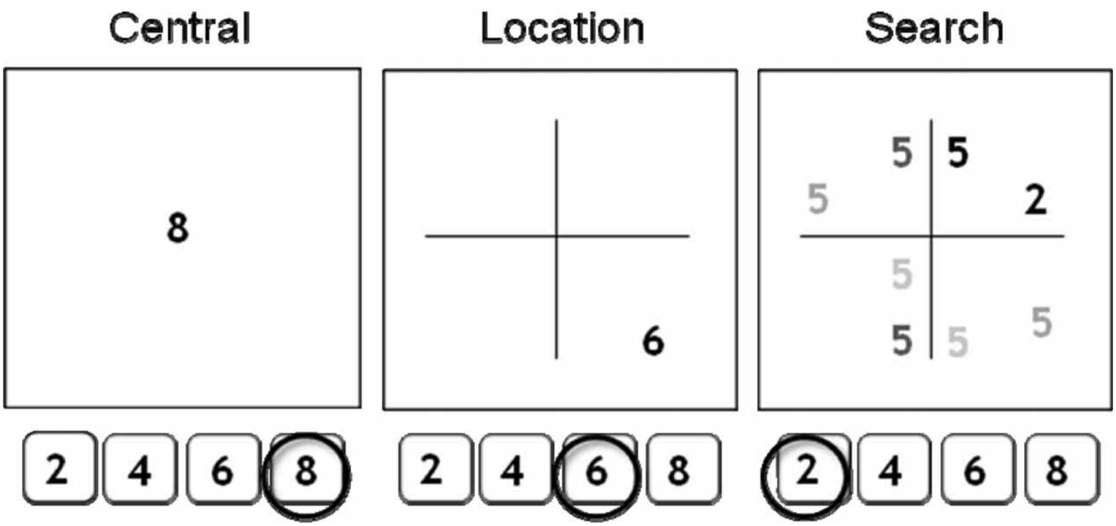

Figure 1. *Representation of the display presented on a trial from the central, variable location, and search conditions. Response keys are represented below, with the correct response circled. Digits appear in different colours, which are represented here as shades of grey.*

Procedure

Participants responded on the identity of the even number (2, 4, 6, 8) by pressing the keys V, B, N, and M with the middle and index fingers of each hand. Training consisted of 12 blocks of 96 trials. With the exception of the test block 11, the remaining blocks contained eight repetitions of a second-order conditional (SOC) sequence (Reed & Johnson, 1994) in which all trials and all possible transitions were equally probable, and in which the next event can only be determined by considering contexts of length 2. The training series was 2–4–2–8–6–4–8–2–6–8–4–6. Each block started randomly at any point within this sequence. Block 11 was structured as a test block, containing four repetitions of this sequence together with four instances of another SOC sequence. The test sequence was generated by interchanging digits 2 and 6, thus producing the series 6–4–6–8–2–4–8–6–2–8–4–2. This sequence is structurally analogous to the training sequence, but predicts a different successor for each context of length 2. The order of the sequences was random over the test block. The two sequences were connected by respecting the second-order structure, so that the first item of each sequence was selected according to the identity of the two previous trials.

The response-to-stimulus interval (RSI) was 200 ms. Error responses elicited a 100-ms tone, but the next item followed any valid response. Short, self-paced rest periods were arranged after each experimental block, where participants were informed about their average RT and percentage of hits.

At the end of the experimental blocks, participants performed a cued generation task, designed to measure learners' ability to predict the more likely successor in each context of length 2. Participants were presented twice with each of the 12 legal contexts. Over the context trials, participants responded in the same way as they did over the SRT task. Over each third trial the target was replaced by either a question mark or a distractor (in the search condition), and participants were instructed to guess the identity of the removed target. Accuracy was emphasized on these trials, but no feedback was provided on generation performance.

Results

The alpha level was set at .05, two-tailed. Greenhouse–Geisser corrections were considered when relevant, but nominal degrees of freedom are reported. For significant effects, partial η^2 are reported as a measure of relative effect size. Error rates were consistently low, amounting to 4.5% of the trials. Responding to test sequences over the test block produced a larger proportion of errors than did responding to training trials over its neighbouring blocks, $F(1, 87) = 23.27$, $\eta^2 = .21$. No other relevant effects were significant in the error analyses, and thus we concentrated the discussion on RT.

RTs on errors as well as the first two trials from each block were discarded. Figure 2 represents the mean RT from all remaining trials averaged for condition and block. Over the test block, mean RTs were separately obtained for training and test sequences.

As is obvious from Figure 2, responding took longer in the search condition than in the central condition, whereas the variable location condition produced intermediate RTs. A 3 × 10 mixed-model analysis of variance (ANOVA) over the training blocks confirmed the effects of condition, $F(2, 87) = 52.47$, $\eta^2 = .55$, and practice, $F(9, 783) = 42.86$, $\eta^2 = .33$. The interaction Condition × Practice was significant too, $F(18, 783) = 4.25$, $\eta^2 = .09$, indicating that practice produced larger improvements in the search condition, probably due to the adoption of efficient strategies to segregate targets from distractors. A planned comparison between search and the control conditions by the end of training (Block 10) still showed a large filtering cost at this point, $F(1, 87) = 69.09$, $\eta^2 = .44$.

Sequence learning was analysed comparing RT to test sequences over Block 11 with RT on the neighbouring blocks (10 and 12). A 3 × 2 ANOVA showed significant effects of condition, $F(2, 87) = 41.64$, $\eta^2 = .49$, and block, $F(1, 87) = 27.01$, $\eta^2 = .24$. The interaction Condition × Block did not reach significance, $F(2, 87) = 2.09$, $p = .13$, $\eta^2 < .05$, suggesting that learning was not significantly modulated by these conditions.

Because the nominal effects of learning were larger for the central condition (61 ms, $\eta^2 = .33$) than for the search (27 ms, $\eta^2 = .27$) and variable location conditions (29 ms, $\eta^2 = .13$), despite the fact that the central condition produced the fastest RT (601 ms, vs. 897 and 672 ms) and the lowest standard deviation ($\sigma_x = 271$, vs. 306 and 341), we were concerned that relevant learning differences might be hidden behind these differences in raw latencies. To control for these differences, we normalized the measures by transforming them into standard scores computed with reference to their own group mean and standard deviation.[2] The analyses conducted on these standard scores produced analogous results, except that the interaction Condition × Group now yielded significance, $F(2, 87) = 3.23$, $\eta^2 = .07$. Helmert contrasts computed on the effect of learning (i.e., on differential scores obtained by substracting performance on the test sequence over the block 11 from the average performance on the training sequence from the neighbouring training blocks) indicated that sequence learning was larger in the central condition than in the other two groups, $F(1, 87) = 6.39$; $\eta^2 = .07$; $p = .013$, whereas there was no difference between the search and the variable location groups, $F(1, 87) < 1$; $p = .79$, see Figure 2, panel B.

Such a difference in learning might be attributed to a larger amount of explicit knowledge produced in the central condition. If this were so, a difference should be found in the cued generation task, but qualitative differences could also arise on the SRT task. As shown by Jiménez et al. (2006), the expression of explicit knowledge tends to be selectively affected by changes in the sequence validity. Our test block allowed us to analyse whether such a decrease in validity could affect participants' reliance on sequence information, since it included four training series interspersed with another four test series. A 3 × 2 ANOVA comparing the *Z* scores in response to the sequential trials from the low-validity block and its neighbouring blocks showed a significant effect of validity, $F(1, 87) = 9.84$, $\eta^2 = .10$, and a significant interaction Condition × Validity,

[2] The aim of this transformation was to control for group differences in mean and standard deviation, while maintaining the original variability attributable to practice or individual differences. That is why we used group statistics to compute these normalized scores.

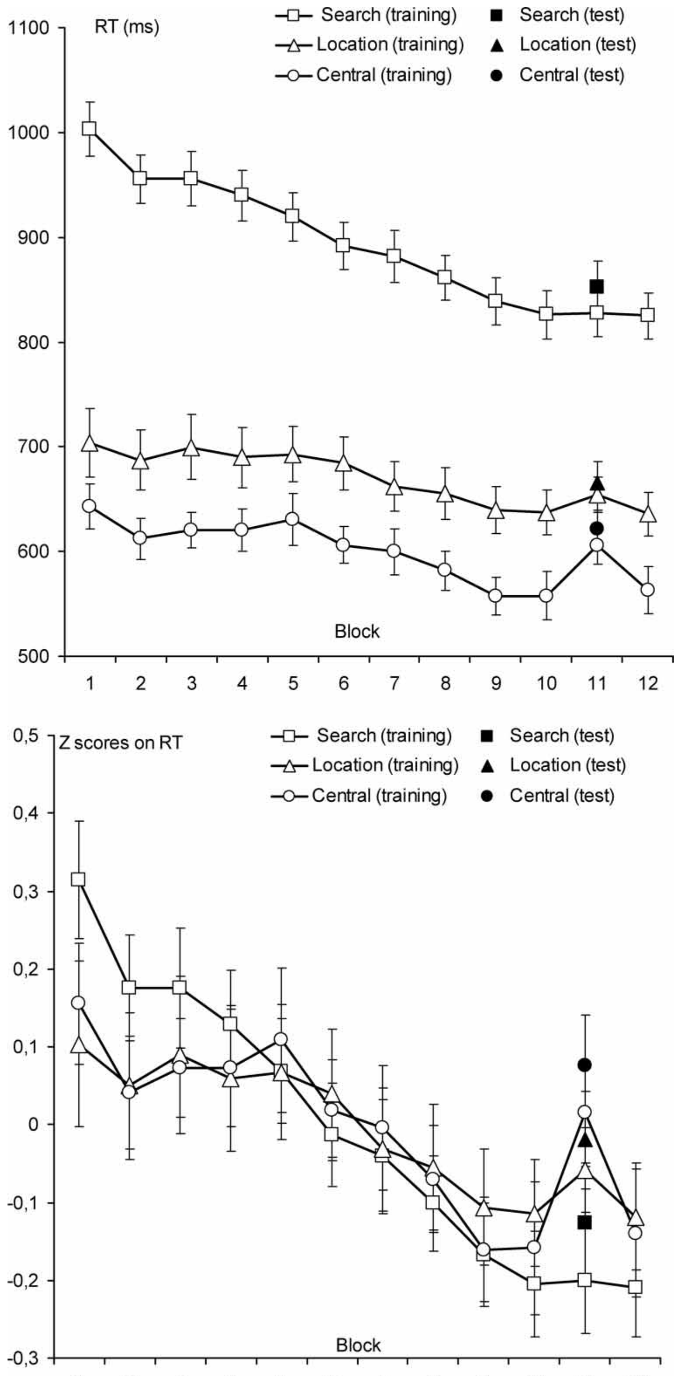

Figure 2. *Mean reaction times (top panel) and Z scores (bottom panel) for correct responses over training (Blocks 1–12) for the search, variable location, and central conditions. On the test block 11, the average responding to training and test sequences are plotted separately. Error bars stand for standard errors.*

$F(1, 87) = 3.66$, $\eta^2 = .08$. As predicted, Helmert contrasts on differential scores showed a significant difference in the effect of validity between the central condition and the remaining groups, $F(1, 87) = 6.58$; $\eta^2 = .07$; $p = .012$, but not a difference between the other two groups, $F < 1$; $p = .39$.

The cued generation task produced convergent evidence on the differences between conditions in amount of explicit sequence knowledge. We computed the proportion of generation trials that completed each context with successors corresponding to either the training or the test sequences. Figure 3 represents these proportions separately for each sequence and condition.

A 3 × 2 ANOVA showed significant effects of condition, $F(2, 87) = 7.84$, $\eta^2 = .15$, and sequence, $F(1, 87) = 7.87$, $\eta^2 = .08$, but not a significant interaction Condition × Sequence, $F(2, 87) = 1.22$, $\eta^2 = .03$. However, Figure 3 suggested that such discrimination was clearer in the central condition (.48 vs. .37) than in the other groups. An individual analysis conducted for the central condition produced a significant effect of sequence, $F(1, 29) = 5.63$, $\eta^2 = .16$, which did not approached significance either in the variable location, $F(1, 29) = 0.84$, $\eta^2 = .03$, or in the search conditions, $F(1, 29) = 1.85$, $\eta^2 = .06$.

Because some of the most relevant results from this study are related to the absence of statistical differences in learning between the variable location and search conditions, we computed the power of this experiment to detect such a Block (2) × Condition (2) interaction using G*Power 3 (Faul, Erdfelder, Lang, & Buchner, 2007).

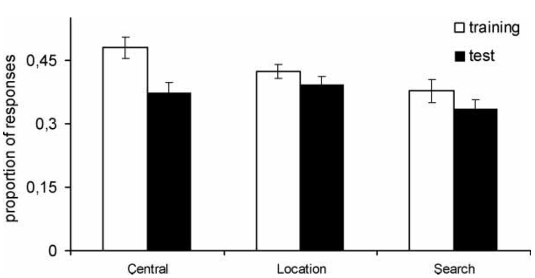

Figure 3. *Proportion of generation responses consistent with training and test sequences, represented separately for the central, variable location, and search conditions.*

The measures of RT were highly correlated in the relevant blocks ($r = .92$), thus increasing the power to detect even small effects in this interaction. The actual power ($1 - \beta$) to detect such a small effect with $N = 60$ amounted to .97, and it remained high ($1- \beta = .85$) even after the small decrease in the empirical correlation ($r = .87$) produced after the Z-score transformation. Therefore, we are confident that the null results obtained in this analysis do reflect a substantial equivalence in learning obtained under the search and variable location conditions.

Discussion

This experiment extended previous results on the influence of selection difficulty in sequence learning, using a complex search condition. Sequence learning was equivalent in a search task in which the target was surrounded by seven distractors and in a similar task without distractors, despite the large filtering cost obtained in the former condition. This strongly indicated that implicit sequence learning does not depend on the resources demanded by the selection task.

In contrast to this equivalence, the results from a central condition indicated that sequence learning might become larger and arguably more explicit when all targets were presented alone at a single location. In this central condition we found that participants were more able to use their knowledge to respond to a cued-generation task and that the expression of their knowledge was more affected by a decrease in the sequence validity, consistent with the claim that the expression of explicit knowledge was more affected by such changes in validity (Jiménez et al., 2006).

A potential account for the differences between the central condition and the remaining groups might have to do with the degree of spatial compatibility existing between stimulus and response locations. In both spatially variable conditions, the location of the targets might enter into a conflict with their assigned responses, and managing this conflict could require additional resources that arguably hinder the acquisition of explicit sequence knowledge. In any case, whatever is the cause of the observed difference between the central condition and the other two groups, the results indicate that implicit sequence learning is resistant to selection demands, and that presenting the targets at variable locations can be useful to control for the acquisition of explicit learning. The resilience of implicit sequence learning to selection demands is relevant from an applied standpoint, because it helps to generalize the findings obtained under highly controlled experimental conditions to more valid ecological settings, but it is also important from a theoretical perspective, as it points to the independence of the underlying processes with respect to whatever resources may be needed to deal with these selection demands.

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