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SEQUENCE CLASS FORMATION FOLLOWING LEARNING OF SHORT SEQUENCES

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The production of 3-item probe sequences by 20 adults was assessed after the participants were trained to respond to three 3-item sequences (A1→A2→A3, B1→B2→B3, and C1→C2→C3). Each sequence was learned progressively according to the successive phase method (1-item phase, 2-item phase, and then 3-item phase). Performance on the 3 probe sequences was consistent with the formation of classes of mutually substitutable sequence stimuli. Elsewhere, learning of these functional classes was enhanced when subjects were trained with a 5-min compared to a 24-hr intersessions delay. These results were discussed according to experimental conditions and acquisition of learning rules knowledge.

Lazar (1977) showed that behavioural processes like those involved in the development of stimulus equivalence also might be involved in the development of generative sequential responding. Such processes would provide a basis for development of syntax, or word ordering. For example, words that occur in the same ordinal position in different word sequences might become mutually interchangeable or equivalent, enabling production of novel word sequences. A child who is taught utterances such as "the big ball," "a red car," and "an old dog," could then produce novel, grammatically correct utterances consisting of various recombinations of words in the trained sequences (e.g., "a big dog," "the old car") without further teaching (cf. Sigurdadottir, Green, & Saunders, 1990).

Relations among stimuli can be studied in or across sequences. When they are studied within a sequence, several properties of a relation of order have been described: irreflexibility, asymmetry, transitivity, and connectedness. These properties will be briefly defined. When subjects learn to respond to five stimuli A1→A2→A3→A4→A5 in that order, the order relation is explicitly not reflexive, as it is not true that A1→A1 (irreflexibility property). The order relation is unidirectional, in that A2→A3 but not A3→A2 (asymmetry). In addition, it is transitive, given that if A2→A3 and A3→A4 then A2→A4 (transitivity). Connectedness has been

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defined by Stevens (1951) as follows: "a relation is connected if it holds between all pairs of items in a specified field. Connected relations are necessary (but not sufficient) to the arrangement of things in a series." For example, if subjects learn to select A1→A2→A3 in this order, then they select A1→A2, A1→A3, and A2→A3, respectively in order.

When relations among stimuli are studied across sequences, the property of interest is the substitutability of stimuli. Thus, several studies have investigated whether training two or more separate sequences of stimuli established stimulus classes consisting of stimuli that occupy the same ordinal position (e.g., first, second, third) in the different sequences. Green, Stromer, and Mackay (1993) refer to these stimulus classes as "sequence classes." Their development is inferred from tests that evaluate whether stimuli from the same ordinal positions in different sequences substitute for one another in untrained sequences or are related conditionally to each other in a matching-to-sample task. The first tactic is to train subjects on two or more sequences separately (e.g., A1-A2-A3-A4 and B1-B2-B3-B4). Following training, presentation of mixed-subsequence probes allows experimenters to evaluate whether stimuli that occupied the same position in different trained sequences substitute for each other, suggesting the formation of sequence classes. Probes were, for instance, mixtures of stimuli from trained sequences, labeled mixed two-stimulus sequences (e.g., A2-B3, B2-A4, and so on). Presentation of probe subsequences also allows relatively unambiguous testing of two properties of an order relation within a sequence, asymmetry and transitivity. In addition, those probes that include the end point stimuli allow for testing whether the order relation holds for all pairs of stimuli, thereby allowing a check on the remaining properties of an order relation (connectedness, irreflexibility). The typical outcome of experiments using this tactic with normally capable humans has been the successful production of novel mixed sequences immediately following establishment of independent sequences (Lazar, 1977; Mackay, Stoddard, & Spencer, 1989; Stromer & Mackay, 1993). This outcome was obtained even when the individual sequences were established by different methods (e.g., sequence A trained as a whole five-stimulus sequence and sequence B established via overlapping adjacent-pair training), and when three separate sequences (A, B, and C), rather than two were trained initially.

The second tactic consists of training subjects with two or more five-stimulus sequences (A1-A2-A3-A4-A5 and B1-B2-B3-B4-B5) and to expose them thereafter to mixed-sequence probe trials (A1-B2-B3-A4-B5). Subjects had to touch the stimuli in the order of their appearance in the baseline sequences. With this tactic, probe performance of some subjects was, however, not consistent with the development of sequence classes (Stromer & Mackay, 1993). Indeed, given a probe trial displaying like stimuli A1, A3, B2, B4, and B5, some subjects touched the stimuli in that order. That is, responses to A stimuli were consistent with training on the A sequence, and responses to the B stimuli were consistent with the trained order, but there was no evidence of stimuli substitutability across sequences that would indicate the formation of sequence classes (i.e., producing the sequence A1-B2-A3-B4-B5).

In this present study, stimulus substitutability was examined by using a slightly modified version of this tactic. It was a simplified version of the design utilized by Sigurdardottir and colleagues (1990). Subjects were first trained with three 3-stimuli sequences (A1-A2-A3, B1-B2-B3, and C1-C2-C3) and were then confronted with mixed three-item displays containing only one stimulus of each baseline sequence, like A1-C2-B3, to test substitutability. This should permit avoiding ordering within rather than across baseline sequences, as reported by Stromer and Mackay (1993). Another particularity of the method was that baseline and probe sequences were trained according to three successive phases. During baseline training on sequence A, subjects learned on a first phase to select stimulus A1, on a second phase stimuli A1 then A2 in this order, and finally on a third phase stimuli A1, A2, then A3. As subjects actively added a novel stimulus at each learning phase, order relations between the stimuli of a sequence should be more robust than with direct learning of a 3-item sequence. Moreover, subjects were trained on baseline sequences on sessions separated either by a 5-min or by a 24-hr delay in order to determine whether order relations established persistently. In most studies, all baseline sequences were trained on a single training session and immediately thereafter subjects were confronted with novel mixed-item displays (Lazar, 1977; Mackay et al., 1989; Stromer, Mackay, Cohen, & Stoddard, 1993).

Elsewhere, the first systematic investigations of the effects of instructions on the transfer of stimulus functions through equivalence classes led to contradictory results. Instructions appeared to facilitate this process in one study (Sigurdadottir et al., 1990), while they would have impeded the transfer of ordinal functions through equivalence classes in another study by the same authors (Green, Sigurdadottir, & Saunders, 1991). However, in natural conditions, at the time when syntax or word ordering develop, children are able to produce novel word sequences without being instructed to do so. Furthermore, adults experience daily stimulus substitutability, not only during language production and comprehension, but also in other activities, like playing an instrument. In light of these considerations, item substitutability was explored by providing only minimal task instructions.

Method

Subjects

Forty six volunteer students (male and female), aged between 20 and 30 years, were recruited at Toulouse 3 University.

Material

Subjects were faced with a computer color screen. Four square targets (3x3 cm) were presented as a 2x2 matrix at the center of the screen. Subjects selected a target by a click on the mouse. Different items were displayed as targets, all squares with 3-cm edges; colored fields (red, green, blue, yellow, black, white), parallel lines (two 0.3-cm large black lines, 0.4 cm apart, centered in a white square and oriented either vertically, horizontally, or diagonally), geometric shapes (black square, triangle, circle, and diamond, each 2 cm in diameter, centered in a yellow square).

All experimental events (stimulus presentation, mouse click detection, darkening of the screen and presentation of a novel configuration) were controlled and recorded continuously by an IBM PC clone. The four items used for each sequence were presented in a different configuration on each trial according to an algorithm for randomizing sequences with the following restrictions. No more than two presentations of either configuration could occur successively, and probability (configuration i) = probability (configuration i+1) = 1/24.

Experimental Procedure

A trial started with the presentation of a pseudorandomly selected four-item configuration and ended when the correct sequence was completed. Each click with the mouse on a target was considered as a response. Repeats on the same item and responses in an incorrect order produced no feedback (free correction procedure). The trial continued, however, an error canceled a partially correct sequence. For example, when subjects responded to items A, B, then D, they had to start over again and perform the correct sequence errorless A, B, C. Thereafter the trial ended and the screen became uniformly gray for 3 seconds. During this interval a counter occurred on the screen and it was implemented by 1 point. Thereafter, a new four-item configuration was automatically generated for the next trial.

Each sequence was trained on a single session, with a duration limited to 45 minutes. The sequence was learned progressively according to the successive phase method. On the first phase, subjects had to respond to the first item alone, on a second phase they responded to two items in the correct order, and finally on the third phase to three items. The learning criterion allowing subjects to progress from one learning phase to the next was fixed at five consecutive errorless trials, that is, five consecutive errorless response sequences.

Preliminary Experiment

Twenty six subjects participated in the preliminary experiment. This experiment was run to determine (a) which of two stimulus-set configurations to use, and (b) whether in the present experimental conditions item substitutability with mixed probe sequences may develop a priori. More especially, we wanted to make sure that, in the experimental conditions described, subjects would remember item identity. Note that subjects progressed rapidly in this task, so that item configurations were presented only briefly, that is, the time period necessary to select the relevant items in the correct order. Subjects learned four 4-item sequences, with the first and fourth sequences being identical (chromatic fields red, blue, green, and yellow). This allowed for exploring whether subjects would recognize items of sequence 1 after learning two additional sequences. The two intermediary sequences were comprised of two additional sets of chromatic fields for half of the subjects (n = 13), while they were comprised of items issued from different categories in the other half (n = 13; series 2: parallel bars oriented either vertically, horizontally, or diagonally; series 3: achromatic geometric forms, square, triangle, circle, and diamond).

Sequence Substitutability (Table 1)

The 20 remaining subjects, that is, those who had not participated in the preliminary experiment, participated in the experiment exploring item substitutability. On the first part of the experiment, subjects learned three different baseline sequences, each comprised of three items so that the fourth item was a distractor item (item 4). In light of the results obtained in the preliminary experiment, items of each sequence were issued from a different category. Sequence A was comprised of chromatic fields (A1, A2, and A3), sequence B of parallel bars (B1, B2, and B3) and sequence C of achromatic geometric shapes (C1, C2, and C3). On the second part of the experiment, items of baseline sequences were mixed as follows: probe sequence 1 (A1, B2, C3), probe sequence 2 (C1, A2, B3) and probe sequence 3 (B1, C2, A3). Distractor items C4, A4, and B4 were presented with probe sequences 1, 2, and 3 respectively. This was to test whether subjects had achieved item substitutability and established sequence classes, that is, whether the items with subscript 1 in the different sequences had become substitutable for one another and similarly for subscript 2 items and subscript 3 items.

Table 1

Alphanumeric Representations of Three Baseline Sequences and Three Probe Sequences Derived from the Former

Training sequences
Baseline sequence A
A1 → A2 → A3 / A4
Baseline sequence B
B1 → B2 → B3 / B4
Baseline sequence C
C1 → C2 → C3 / C4
Testing sequences
Probe sequence 1
A1 → B2 → C3 / C4
Probe sequence 2
C1 → A2 → B3 / A4
Probe sequence 3
B1 → C2 → A3 / B4

Note. A4, B4, and C4 represent irrelevant distractor items any one of which was presented together with three relevant items as a four-item configuration.

This ability was tested in one group of subjects ($n = 11$) learning the baseline sequences on massed sessions, that is, separated by a 5-min delay (filled by responding to a questionnaire, see below), and a second group of subjects ($n = 9$) submitted to distributed learning sessions, separated by a 24-hour delay. Twenty four hours after learning the last baseline series, both groups of subjects were confronted on probe sessions to the compound lists with a 5-min interval separating successive probe sessions.

Instructions and Questionnaire

At the beginning of the experiment, subjects received the following instructions: "It's a computer game. Touch the targets with the mouse until they disappear. After three seconds, targets reappear and you start over again. Try to find the most simple solution to the game."

Participants made a verbal report following training on each baseline sequence and answered the following questions:

Have you discovered the rules of this amusement?
If so, what were they?
Can you recall the item sequence?
Have you encountered problems?
If so, what kind?

For those subjects who could not recall the sequence, the experimenter recalled it to ensure fair comparisons. At the end of the experiment, subjects were asked the following question: "Did you notice something particular concerning the three last sequences?".

Results

Preliminary Experiment (Table 2)

The number of errors per trial was comparable for both groups during training on sequence 1. It decreased during testing of the fourth sequence which was identical to the first one. A three-way ANOVA of factors group x phase x sequence revealed a significant interaction between group and sequence, $F(1, 72) = 6.54$, $p = 0.001$. A subsequent post hoc Newman-Keuls test showed that the interaction resulted from a significantly reduced number of errors during testing on the fourth sequence by subjects trained with items from different categories, $p < 0.02$. All other experimental conditions being identical between groups, the results suggest an interference between sequences when all of these were comprised of items issued from the same category (chromatic fields).

In summary, the results suggest, though indirectly, that recognition of sequence 1 items was achieved at least partly when each of several stimulus sets used were issued from different item categories. Therefore, baseline sequences used in the next experiment were comprised of different categories (colored squares, parallel bars, and geometric shapes respectively for baseline sequence A, B, and C).

Table 2

Number of Errors per Trial during Learning of First and Fourth Sequences

	Different categories	Same category
Sequence 1	4.28 (+/-0.88)	3.19 (+/-0.69)
Sequence 4	0.20 (+/-0.07)	0.42 (+/-0.10)

Note. Intermediary sequences were comprised of items issued from the category other than those of sequences 1 and 4 (same category) or of the categories different from sequences 1 and 4 (different categories).

Sequence Substitutability

Mastery of baseline sequences A, B, and C was achieved in a mean number of 23 (+/-4.2), 27.3 (+/-6.2), and 24.9 (+/-1.6) trials for subjects trained on massed sessions and 36.2 (+/-7), 24.9 (+/-1.7), and 20.1 (+/-4.2) trials for those trained on distributed sessions. Statistical analysis showed no between-group difference, indicating comparable performance during baseline training for both groups. Results obtained with tests investigating item substitutability revealed that performance differed between the two groups. Analysis of items selected on trial beginning revealed an effect of item for each mixed sequence, $F(3, 153) = 706.19$, $p = 10^{-5}$, $F(3, 153) = 985.5$, $p = 10^{-5}$, $F(3, 153) = 1832.2$, $p = 10^{-5}$, respectively, indicating that on all probe sequences subjects chose the first item (A1, B1, or C1) always more often than either other item to start trials. Between-group comparisons (cf. Table 3) revealed an

Table 3

Percentage of Correct Responses on First Item of Each Probe Sequence Following Baseline Training on Massed and Distributed Sessions

	A1-B2-C3	C1-A2-B3	B1-C2-A3
Massed sessions	74.11 (+/-3.38)	89.46 (+/-10.17)	94 (+/-10.41)
Distributed sessions	82.22 (+/-2.22)	81.9 (+/-8.33)	74.37 (+/-3.85)

interaction between group and item, $F(3, 153) = 6.68$, $p = 0.0003$, indicating that subjects trained on massed sessions performed slightly, but significantly, more responses on the first item (A1, B1, or C1) compared to subjects of the other group, $p = 0.0002$. Further, we investigated whether subjects rapidly identified the item which they had to add to the subsequence learned in the prior learning phase (cf. Table 4). On the two-item learning phase, we computed the rate of transitions performed between the previously learned item X1 and to-be-added item X2 (transition X1-X2). This rate was compared to chance level performance which corresponded to 33% given that subjects selected the new item among three items in this learning phase. Similarly, on three-item learning, we compared the rate of the correct last transition X2-X3 to chance level, corresponding to 50%. During two-item learning, the mean

Table 4

Rate of Production of Correct Transitions in Second and Third Learning Phases for Subjects with Massed Sessions and Distributed Sessions Training

Massed sessions	A1-B2-C3	C1-A2-B3	B1-C2-A3
Phase 2	53.9 (+/-7.1)	69.2 (+/-10.5)	70 (+/-8.2)
Phase 3	84.6 (+/-7.9)	95 (+/-5)	100 (+/-0)
Distributed sessions	A1-B2-C3	C1-A2-B3	B1-C2-A3
Phase 2	56.94 (+/-11.37)	51.98 (+/-21.26)	59.25 (+/-10.43)
Phase 3	86.25 (+/-7.86)	79.62 (+/-8.23)	69.31 (+/-6.83)

Note. Data are for the correct transition in the second learning phase (A1→B2, C1→A2, and B1→C2) and the correct last transition in the third learning phase (B2→C3, A2→B3, and C2→A3), for subjects trained with massed sessions (upper panel) and distributed sessions (lower panel).

rate of the correct transition reached 62% and 55% (mean across the three probe sequences). On the three-item phase, the corresponding rates were 95% and 77%. Both, following training on massed and distributed sessions, a significant effect of phase was shown, $F(2, 27) = 30.66$, $p < 0.0000$ and $F(2, 24) = 7.30$, $p = 0.0033$, respectively. It corresponded to an increased rate of the relevant last transition on three-item compared to two-item learning, $p = 0.0012$ and $p = 0.0077$, respectively. Between-group differences on Phase 2, $F(1, 17) = 4.51$, $p = 0.048$, and on Phase 3, $F(1, 17) = 6.17$, $p = 0.00237$, indicated enhanced rates to the correct transition for all probe sequences with massed compared to distributed sessions, $p < 0.0002$.

Discussion

In this experiment, subjects' performance was consistent with the development of sequence classes in the present conditions. This result contrasts with those reported by Stromer and Mackay (1993) who observed no evidence of substitutability of stimuli across sequences. Two reasons may explain this difference of performance. First, baseline sequences used in the present study comprised fewer items so that only one item of each baseline sequence was used to form probe sequences. In contrast, in Stromer and Mackay's study (1993), two or three items of the same baseline sequence were presented in a given probe sequence. Second, the experimental procedure developed here probably fitted closer to natural conditions. Indeed, learning of several word sequences might result in the emergence of classes of words that served a common function in the sequences as in the following example. Once a child has learned sentences such as "the big ball," "a red car," and "an old dog," it may have formed three sequence classes: one containing the articles, one the adjectives, and a third one including the nouns (Lazar, 1977). Each mixed sentence that the child may thus construct would contain one element only of each class.

Subjects of the two groups started trials almost exclusively with a response to the correct first item, indicating that they had established a first-position class. Establishment of a second-position class seemed to be less evident, as indicated by a correct response to the corresponding stimuli in the second position in about only half the trials. Finally, third-position class seemed clearly established, because selection of the correct stimuli in this position largely outnumbered chance level. This stimulus class was best identified by subjects trained on massed sessions, as evidenced by a significantly larger rate of correct choices in this position compared to subjects trained on distributed sessions. These results seem to indicate that establishment of stimulus classes was easier for the first and the last stimuli of baseline sequences than for intermediary stimuli. Stromer et al. (1993) have shown that subjects with mental retardation made repeated errors on subsequences involving stimuli that occupied the second and third position of a five-term baseline sequence (e.g., A2-A3 and A3-A4). A serial position effect was also reported for response latencies (Holcomb, Stromer, & Mackay, 1997). After training with a six-term sequence (A-B-C-D-E-F), the shortest response latencies usually occurred on trials with end-anchored sequences (A-B and E-F), whereas latencies on trials with the embedded (B-C, C-D, and D-E) sequences were longer.

These data clearly rule out a chaining account in explaining baseline sequence learning. According to this account, successive responses are controlled by a specific discriminative stimulus produced by the immediately preceding response. On a trial with the three-term A sequence, for example, the presence of A1 would be one likely stimulus that would control selection of A2. Such specificity of discriminative control required by a chaining account is incompatible with subjects' successful performance on mixed A/B/C sequences. Because the A, B, and C stimuli had never appeared together in training, the contingencies necessary to establish such mixed chains had never occurred. These outcomes suggest that subjects' baseline behavior was based on relations among the stimuli and that these relations reflected stimulus control by the relative as well as the absolute positions of the stimuli in the baseline sequences (D'Amato & Colombo, 1988; Straub, Seidenberg, Bever, & Terrace, 1979; Straub & Terrace, 1981; Terrace, 1986). Furthermore, the mutual substitutability of the A, B, and C stimuli on mixed three-term testing sequences supports the idea that subjects had learned three functional classes, each consisting of an X1, X2, and X3 stimulus that occupied the same serial position in the sequences trained directly.

The hypothesis of stimulus class formation in the present conditions raises then the question whether subjects also formed a stimulus class of distractor items. In other words, if the distractor items were clearly identified from the sequence stimuli by the end of training, then the chance probabilities on the two-item and three-item transitions were not 33% and 50% respectively. Rather, in this case they would be 50% and 100% respectively. Results showed that participants in the massed training sessions made 95% correct selections and those in the dispersed training group, 77%. Accordingly, the former would have established a stimulus class of distractors, thereby confirming previous studies (Sigurdardottir et al., 1990). In contrast, when training sessions were dispersed, distractors had apparently not become a stimulus class. This difference may be related to the training conditions. Perhaps the dispersed training implied to the participants that each training sequence was part of a separate experiment, whereas massed training implied one big experiment.

Alternatively, this and other performance differences could be caused by differences in rule learning. Indeed, training on massed sessions resulted also in enhanced learning of functional classes of relevant items. Given that subjects received only minimal instructions they had to discover the rules governing training on successive phases, the criterion of progression from one phase to the next phase, in addition to item identification and sequentiation. Analysis of subjects' verbal reports revealed that all subjects trained with massed sessions readily verbalized the training rules after training on the second baseline sequence, whereas this knowledge was achieved after training on the last baseline sequence by those subjects trained on distributed sessions. In other words, acquisition of rule knowledge was favored when successive training sessions were separated by a short (5 min) rather than a long delay (24 hr). Sigurdadottir et al. (1990) reported a difference between subjects instructed to training rules and subjects not instructed. For noninstructed subjects a repeated exposure to training and testing contingencies was necessary to lead to a final performance level comparable to that obtained by instructed subjects. In light of this finding one might speculate that with distributed sessions subjects need to be exposed to a larger number of training and testing sequences to achieve comparable performance than those trained on massed training sessions. This speculation awaits, however, further confirmation.

The results demonstrate that adults are able to form order classes even with minimal instructions and in the absence of any feedback consecutive to responses. They thus confirm and extend previous findings revealing item substitutability described with different methods (Green et al., 1993; Lazar, 1977; Mackay et al., 1989; Stromer & Mackay, 1993). A large number of subjects was used in the present study thereby permitting us to generalize to some extent the substitutability principle and the establishment of sequence classes. This statistical approach was complementary to those experiments performed on few subjects and presenting results individually (Green et al., 1991, 1993; Holcomb et al., 1997; Maydak, Stromer, Mackay, & Stoddard, 1995; Sigurdadottir et al., 1990).

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