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Is it really search or just matching? The influence of Goodness, number of stimuli and presentation sequence in same-different tasks

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Abstract The Goodness of Garner dot patterns has been shown to influence same-different response times in a specific way, which has led to the formulation of a memory search model of pattern comparison. In this model, the space of possible variations of each pattern is searched separately for each pattern in the comparison, resulting in faster response times for patterns that have fewer alternatives. Compared to an alternative explanation based on stimulus encoding plus mental rotation, however, the existing data strongly favor this explanation. To obtain a more constraining set of data to distinguish between the two possible accounts, we extended the original paradigm to a situation in which participants needed to compare three, rather than two patterns and varied the way the stimuli were presented (simultaneously or sequentially). Our findings suggest that neither the memory search nor the encoding plus mental rotation model provides a complete description of the data, and that the effects of Goodness must be understood in a combination of both mechanisms, or in terms of cascades processing.

Keywords Same-different task · Garner dot patterns · Memory search · Perceptual Organization

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1 Introduction

In our visual surroundings, we may experience that some shapes are more regular, more organized, or simply 'nicer' than other ones. The Gestalt psychologists introduced the term 'Prägnanz' to refer to such impressions, as a way to communicate the overall 'Goodness' of an object. Several studies have aimed to quantify this Goodness. A stimulus set that has been used regularly for this purpose is illustrated in Figure 1A. This figure shows a set of dot patterns that is obtained by placing five dots on an imaginary three by three grid such that each row and each column in the grid contains at least one dot. The influence of the Goodness of these dot patterns on human behavior has been examined in various experimental tasks. When asked to rate the Goodness of each pattern on a 1-7 or 1-9 scale (Garner and Clement, 1963; Lachmann and Geissler, 2002), participants tend to order the stimuli like in Figure 1A, with high Goodness ratings for the stimuli shown in the top of the figure and low Goodness for those presented at the bottom.

As may be noted, the patterns are organized into three different clusters. Evidence for such clusters was obtained by asking participants to group the stimuli into sets of similar items (Garner and Clement, 1963). The results show that patterns of high Goodness are generally placed in clusters of a smaller size. Findings like these and considerations from information theory led to the concept of 'Equivalence Set Size' (ESS), in which patterns of higher Goodness have a smaller ESS (Figure 1A) and are more redundant in terms of information theory. The number assigned to an ESS reflects the number of patterns that can be obtained after 'reflection and rotation' (R&R) transformations, involving 90 degrees rotations and mirror reflections along the horizontal and vertical axis (Garner and Clement, 1963; Lachmann and Geissler, 2002). Three ESSes emerge (Figure 1A). In the $ESS = 1$ cluster there are two patterns with high levels of Goodness ratings (Garner and Clement, 1963; Lachmann and Geissler, 2002). The ESS of these dot patterns equals one, because after R&R transformations, the same pattern is obtained (Figure 1A, top). Items in the second set of patterns (Figure 1A, middle) have an ESS of 4, meaning that four possible versions can be created by applying R&R transformations. Finally, there are seven patterns that generally receive the lowest Goodness ratings. These patterns have an ESS of 8 (Figure 1A, bottom), meaning that rotations and reflections of these patterns result in a set of eight different versions of the pattern.

Further evidence for the importance of the ESS in perception has been obtained from response times experiments. For example, Clement and Varnadoe (1967) found that sorting times are longer for stimuli with a larger ESS. Furthermore, response times to individual patterns or pairs of patterns have been shown to increase with ESS (Checkosky and Whitlock, 1973; Garner and Sutliff, 1974; Lachmann and Geissler, 2002; Lachmann and van Leeuwen, 2005a,b, 2007a, 2010; Pomerantz, 1977). An often used paradigm in these experiments is the categorical same-different task. In this task, participants are presented with two dot patterns and are asked to decide whether these patterns are the

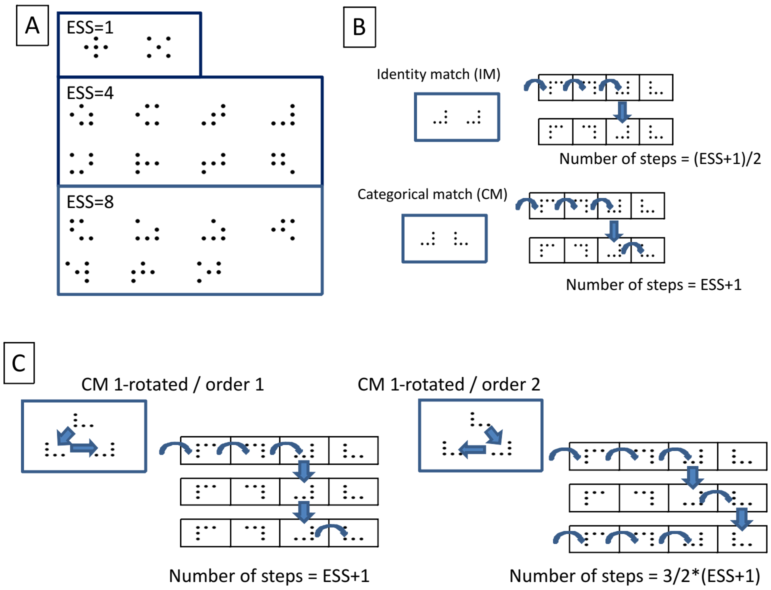

Fig. 1 [A] Dot patterns from Garner and Clement (1963), classified according to their Equivalence Set Size (ESS). The stimuli in the $ESS = 1$ category are invariant under rotation and reflection (R&R) transformations. Stimuli in the $ESS = 4$ category yield four distinct patterns after R&R. Patterns with an ESS equal to eight yield eight different patterns after R&R. [B] Illustration of the memory search model ('Model C' from Lachmann and Geissler (2002)) for the same-different task. For stimuli that are identical both in shape and orientation, an average of $(ESS + 1)/2$ search steps are required for processing. For stimuli identical in shape but different in orientation, an average of $ESS + 1$ search steps are required. [C] When extending the model to 3 stimuli, two CM conditions arise: One in which two patterns have the same orientation and one a different orientation (CM - 1 rotated) and one CM-condition in which all three patterns have a different orientation (CM - 2 rotated). Search times in the former CM-condition (CM - 1 rotated) depend on the order in which the stimuli are considered. When the two identical stimuli are processed in sequence, $ESS + 1$ search steps are required to locate all stimuli. When the differently orientated patterns are compared first, the number of search steps is expected to increase to $\frac{3}{2} \cdot (ESS + 1)$. The average search time in the CM-1 condition will be weighted version of these two search times.

same, regardless of their orientation (Lachmann and Geissler, 2002; Lachmann and van Leeuwen, 2005a, 2010). Response times increase as an approximately linear function of the ESS, both when the patterns are identical in shape and in orientation ('identity match' or IM) and when the patterns are R&R variations of the same pattern ('categorical match' or CM), as shown in Figure 2 in which the data from (Lachmann and Geissler, 2002) are replotted (white symbols). IM and CM response times differ in their overall magnitude (CM responses are slower) and the associated slope of the function of ESS (steeper slope for CM pairs). These data led to the formulation of a memory search model. The basic idea of the model is that visual stimuli are automatically perceived as categories rather than individual items. In the particular case shown in Figure 1C, the presentation of a dot pattern automatically leads to the activation of all possible versions of the pattern. This means that when presented with an $ESS = 4$ pattern, all four versions of the pattern of that set are automatically activated, whereas for an $ESS = 8$ pattern, eight possible versions will be activated. The response time is a function of the time needed to search these different versions.

This process of automatically activating and searching all possible orientational versions of a pattern was formalized in a computational model (Lachmann and Geissler (2002), 'Model C'; see Figure 1B for an illustration). To see how this model works, consider the situation in which participants are performing the categorical same-different task on a pair of the same $ESS = 4$ patterns. This task leads to the following memory search. To look up the first item, a search is performed through the array of possible versions, arranged in an arbitrary order. Because the item can be at any of the locations in the array of elements, the search for the first item is expected to complete after an average of $\frac{(ESS+1)}{2}$ steps, if it is assumed that search is self-terminating, i.e., it ends when the target has been found. In order to retrieve the next item, the search process continues at the same location in the array (Figure 1B; shown as a separate, but identical array, for illustration purposes). As a consequence, no additional search steps are required for an identity match (where the two patterns are identical in shape and orientation). For a categorical match (where the two patterns have the same shape but differ in orientation), the search needs to continue, resulting in additional expected number of $\frac{(ESS+1)}{2}$ steps. Thus, for a categorical match this leads to a total of $2 \cdot \frac{(ESS+1)}{2} = ESS + 1$ search steps. If instead a non-match ('NM') trial is presented, in which two patterns that differ in shape are shown, the number of expected search steps is a combination of the two individual ESSes, resulting in a total of $\frac{(ESS_1+ESS_2)}{2}$ expected search steps.

The memory search model was found to be accurate in its predictions of response times in the same-different task, as illustrated in Figure 2A, even when the response times of individual participants were considered separately (Lachmann and Geissler, 2002). Importantly, the model accurately predicts the non-additive effects of the ESS and pattern orientation (comparing IM and CM conditions), with different slopes of the best fitting lines through the data of the $ESS = 4$ and $ESS = 8$ categories (Figure 2). Such non-additive (i.e., non-equal slopes) effects led to the rejection of an alternative model, in which patterns with higher ESS values are encoded more quickly and mental rotation is performed for CM pairs. To examine the issues with this alternative model, Figure 2B plots the predictions based on additive encoding and mental rotations times ('encoding+mental rotation' model) in comparison to the data by Lachmann and Geissler (2002) (for details of the model, see the appendix). Encoding times for these predictions were estimated from the response times in the IM conditions, and the mental rotation time was estimated

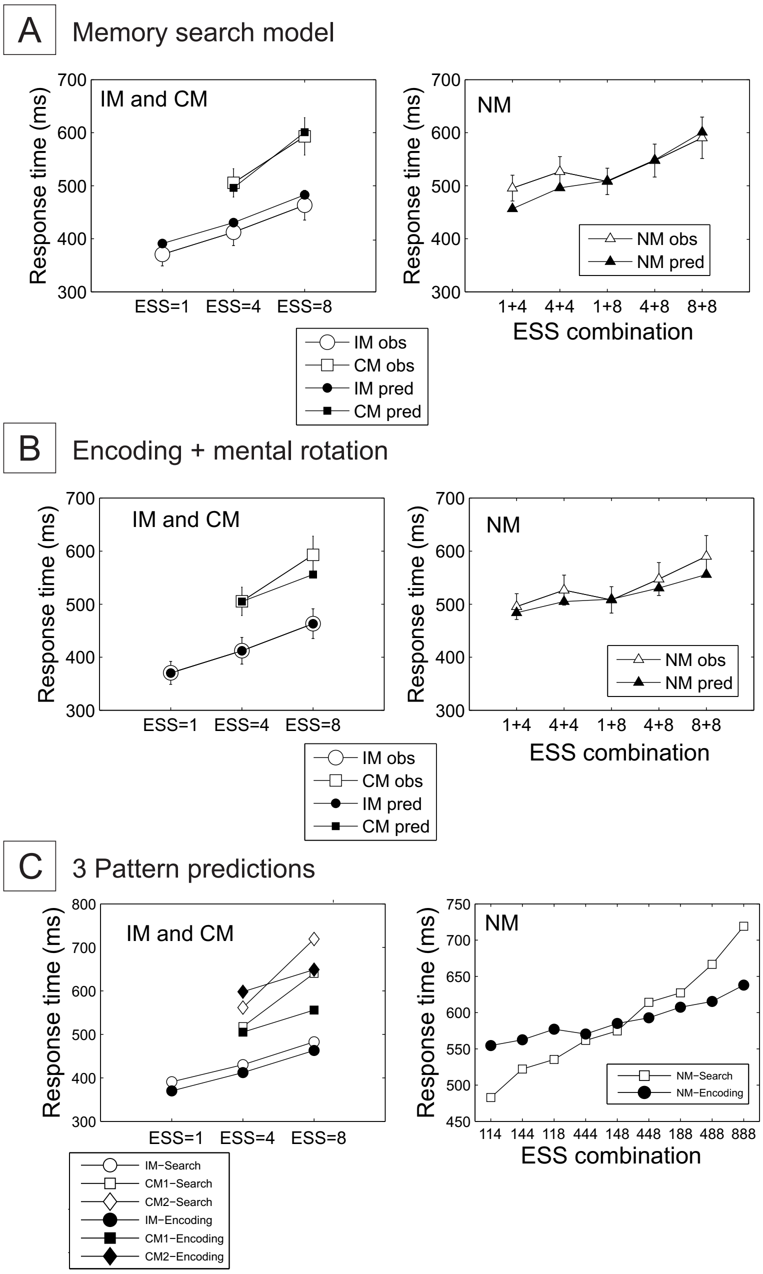

Fig. 2 Comparison of the data replotted from Lachmann and Geissler (2002) (white symbols) and the model predictions (black symbols). [A] Predictions from the memory search model (Lachmann and Geissler, 2002). [B] Predictions on the basis of encoding time plus mental rotation assumptions. [C] Predicted pattern of results for when three rather than two patterns need to be compared. For these plots, we used the estimates from subplots [A] and [B], so the vertical scale may be different from when the actual data from the experiments will be used. Note that for the purpose of illustration, data points have been connected, not meaning to suggest that they fall on a continuum.

from the difference between the IM and CM response times[1]. Mental rotation is assumed to be required for the CM conditions, but also for the NM conditions, in this case in order to ascertain that no match is obtained after rotation and reflection. While the encoding + mental rotation model fails to predict the non-additive effects of ESS and rotation (it produces equal slopes for $ESS = 4$ and $ESS = 8$ for the IM and CM data), the remainder of the predictions fit the observed response times well[2]. Furthermore, the encoding + mental rotation model appears to be more accurate in predicting the non-match data than the memory search model. This suggests that by generating exact predictions for the two models, the advantage for the memory search model is no longer as strong as it previously seemed to be (Lachmann and Geissler, 2002). Additional data have since become available, including data from a physical sameness task in which participants decide whether two patterns are identical in shape *and* orientation (Lachmann and van Leeuwen, 2005b), and data showing the influence of the relative frequencies of different ESS categories in the experiment (Lachmann and van Leeuwen, 2005a,b). While some of these data pose difficulties for the encoding + mental rotation model (e.g., an ESS effect in the CM category in the physical same-different task; Lachmann and van Leeuwen (2005b)), also the memory model requires additional assumptions in order to explain these results.

The aim of the present study is to perform a more stringent test of the two models. Since the main difference between them resides in the non-additive effcts of the ESS and orientation, the models could be contrasted more effectively on a data-set for which a greater range of non-additive effects is predicted. Such a data set is obtained by increasing the number of patterns on each trial from two (Lachmann and Geissler, 2002) to three (present study), leading to a marked increase in the number of possible stimulus combinations (particularly in the non-match condition). As a consequence, the new data set will contain many more data points to be explained by the two models. As in Lachmann and Geissler (2002), IM, CM and NM conditions will be used and the ESS of each individual pattern will be varied between 1, 4, and 8. Increasing the number of patterns to three leads to the same number of IM conditions, but the number of CM conditions increases from two to four. These four CM conditions consist of two conditions ($ESS = 4$ and $ESS = 8$) in which two of the patterns have the same orientation and the third pattern a different orientation ('CM - 1 rotated' or 'CM1'), and a further two conditions in which the same-shape patterns all have a different orientation ('CM

[1] For the estimation of the mental rotation time, the $ESS = 4$ response times were used, but this is an arbitrary choice. Other possibilities would have been the average of the $ESS = 4$ and $ESS = 8$ differences or an estimate on the basis of IM, CM and NM response times.

[2] Note that in its current form, the encoding + mental rotation model uses more free parameters than the memory search model, namely three parameters for the encoding time and an additional parameter for the mental rotation time. The memory search model only uses two parameters to fit the search steps to response time (the intercept and slope). The number of parameters for the encoding + mental rotation model can be reduced by using a linear function of the ESS category to estimate the encoding time.

- 2 rotated' or 'CM2'). Whereas with two patterns there were five non-match ESS combinations (Figure 2A and 2B), the use of three patterns led to nine different ESS combinations of different shapes (Experiment 1; Figure 2C). By allowing triplets to contain two identical shapes (IM or CM pairs), another thirteen ESS combinations are obtained (Experiment 2). The consequences for the model predictions for Experiment 1 are illustrated in Figure 2C. As for the two-pattern case, the memory search model predicts an interaction between ESS and Orientation for the IM and CM conditions, with a larger slope when one pattern is in a different orientation (CM1) and an even steeper slope when all three patterns have a different orientation (CM2). In contrast, the encoding plus rotation model predicts no interaction between ESS and Orientation. For the non-match (NM) conditions, the memory search condition predicts a steeper slope than the encoding plus rotation model when all three patterns differ in shape. Further predictions for the NM condition are obtained when two of the three patterns can be identical, but we will defer their description when discussing the data of Experiment 2. As in Lachmann and Geissler (2002), participants performed a categorical same-different task, in which they were asked to determine whether the three patterns were *all* the same, irrespective of their orientation (IM or CM) or not (NM). The use of three patterns rather than two leads to another possible interesting aspect. Namely, two possible strategies are possible in the non-match trials. In the first strategy, participants respond as soon as they have concluded that two of the patterns are different. Alternatively, they may examine all three the patterns before providing a response. These two strategies will be considered in more detail for Experiment 2.

2 Experiment 1

In Experiment 1, participants were shown triplets of dot patterns on a computer screen and asked to decide whether these are all identical in shape, regardless of their orientation. By using three dot patterns (rather than two, as in earlier studies), a stronger test is obtained to distinguish between memory search and encoding + mental rotation mechanisms.

2.1 Methods

Participants. A total of 19 participants (15 female, 4 male, aged between 18 to 25 years) took part in the experiment. Participants were students of the University of Aberdeen and participated voluntarily without receiving reimbursement. They all provided written consent for their participation in the study, which was approved by the local ethics committee.

Apparatus. The experiment was conducted on a dual-core Pentium PC (Dell) with a 19 inch LCD screen and a standard keyboard. The PC was set up in an experimental room illuminated with fluorescent light. Stimuli were presented using the OpenSesame software package (Mathôt et al, 2012).

Stimuli. Images each containing five black dots (1.72 cd/m^2 in luminance) on a white background (156.0 $cd/m2$ in luminance) served as the stimuli. The black dots were arranged on a virtual three by three grid, such that each row of the grid contained at least one dot (for examples, see Figure 1A). There were two ($ESS = 1$), eight ($ESS = 4$) and seven ($ESS = 8$) base patterns, which after rotation and reflection led to two ($ESS = 1$), $8 \cdot 4 = 32$ ($ESS = 4$), and $7 \cdot 8 = 56$ ($ESS = 8$) dot patterns. On each trial, three of these dot patterns (each measuring 4.5 degrees of visual angle in width and height) were presented simultaneously on a virtual circle with a radius of 10 degrees of visual angle around the fixation point, with one dot pattern presented above fixation and two dot patterns left and right below fixation (see Figure 3A).

Design. Three different conditions were used. In the 'identity match' (IM) condition, the three dot patterns presented on each trial were all the same in shape and orientation. In the 'categorical match' (CM) condition, there were two subcategories. In the 'CM - 1 rotated' subcategory, two of the three patterns that were identical in shape, had an orientation that was different from the third pattern. In the 'CM - 2 rotated' subcategory, all three patterns of the same shape had a different orientation. Finally, in the 'non-match' (NM) condition, all three patterns were different in shape.

Participants each conducted 172 experimental trials, preceded by 16 practice trials (randomly drawn from the experimental trials). There were 36 IM, 48 CM and 88 NM trials, resulting in similar numbers of required left-key and right-key responses and similar numbers of trials for each ESS combination. IM trials contained twelve trials from each of the different ESS categories (1, 4, or 8). CM trials had equal numbers of $ESS = 4$ and $ESS = 8$ trials. The NM condition included equal numbers of the different combinations of the $ESS = 1$, $ESS = 4$ and $ESS = 8$ categories.

Earlier studies (Lachmann and Geissler, 2002; Lachmann and van Leeuwen, 2005a,b) ensured that each combination of individual patterns was presented in equal proportions of trials. This requirement in terms of individual stimuli rather than ESS categories, however, leads to designs with many trials and long testing times. Here, we make use of the finding by Lachmann and van Leeuwen (2005a) that instead of the frequency of the individual patterns, it is the relative frequency of ESS categories that matters. We therefore constructed our design on the basis of ESS categories and then, for each participant and each trial, randomly selected a stimulus from the relevant ESS category. For example, if the trial was a non-match trial with a combination of $ESS = 1$, $ESS = 1$ and $ESS = 4$ stimuli ('1-1-4' or '114' in the data plots to follow), two different $ESS = 1$ stimuli would be shown (since in the non-match condition three different shapes were used), together with a randomly selected $ESS = 4$ category stimulus in a randomly selected orientation. In addition to randomly selecting the individual stimuli, the position of the three stimuli at the three

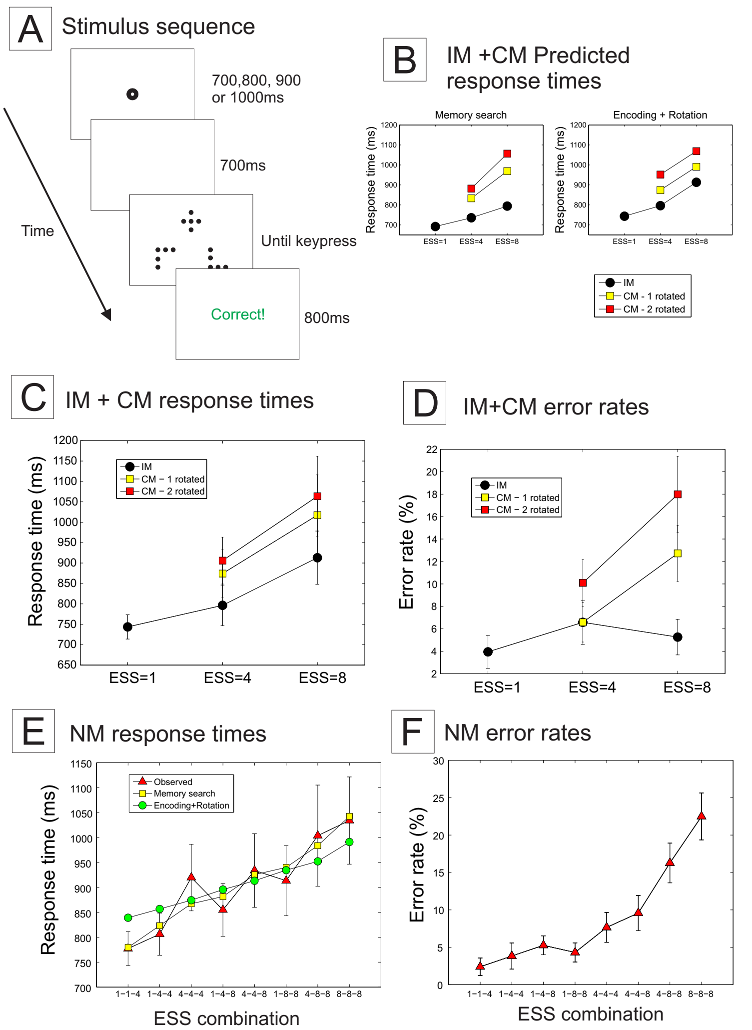

Fig. 3 *Stimulus sequence and results of Experiment 1.* [A] Stimulus sequence. On each trial, participants were presented with a sequence of a fixation point (duration randomly selected between 700 and 1000ms), a blank screen (for 700ms), the three dot patterns (until key-press), and feedback on the accuracy of the given response (for 800ms). [B] Predicted response times patterns (see also Figure 2) for the memory search model (left) and the encoding + mental rotation model (right) for the IM and CM conditions (predictions for the NM conditions are provided with the experimental data). [C] Average response times in the IM and CM conditions for the different ESS categories and the different orientation conditions (see main text). [D] Error rates in the IM and CM conditions across ESS categories and orientation conditions. [E] Response times in the non-match conditions for each of the ESS combinations, in comparison to those predicted on the basis of memory search and a combination of stimulus encoding plus mental rotation.[F] Error rates in the NM conditions. The error bars show the standard error of the mean.

different positions on the screen was also randomly chosen for each trial and participant. Finally, the order of the different trials was randomized across participants.

Procedure. Before taking part, participants were informed about the procedure of the experiment by means of an information sheet and a verbal instruction, after which they signed an informed consent sheet. The key points of the instruction were then repeated on the screen, and the practice block was started. Participants responded by pressing the "P" key, located on the right of the computer keyboard if they thought *all* the patterns were the same (regardless of their orientation) and by pressing the "Q", located on the left of the computer keyboard if they thought the patterns were different. All participants used this mapping of the responses, meaning that in the model predictions a separate intercept in the regression equation may be required to map search steps to response times in the non-match condition (to model a possible delay due to responding with the non-dominant hand). Participants were asked to respond as quickly and accurately as possible. After the practice block feedback about the average response time and accuracy was provided, and the experimental block was started. The experimental block was split in four sections by three short breaks. After a minimum of 10 seconds during feedback on the average response time and accuracy was provided, participants could continue with the block. After the experiment, participants were debriefed about the purpose of the study both verbally and with a take-home debriefing sheet. The entire procedure lasted between 15 and 20 minutes.

Data analysis. Participants all stayed well below the 25% overall error rate in the IM+CM conditions, which we set as the criterion for exclusion, and therefore all participants were kept in the data analysis. Average response times, measured from the onset of the three stimuli, were computed for each participant and condition after removing incorrect responses (on average 9.0% of data removed for both IM+CM and NM data) and exceptionally slow and fast responses (two standard deviations above and below the mean for each participant across conditions; leading to the removal of a further 3.4% and 3.9% of the data of the IM+CM and NM data, respectively). To examine the feasability of this data filtering procedure, the outcomes were compared to an analysis in which we used median response times, which tend to be less susceptible to outliers. Because an identical pattern of results was obtained for both measures, we here report only the average response times, in agreement with earlier studies (Lachmann and Geissler, 2002; Lachmann and van Leeuwen, 2005a,b). For comparisons across multiple conditions and factors, a univariate repeated measures analysis of variance (ANOVA) was used, applying a Greenhouse-Geisser correction where appropriate (i.e., a significant violation of the sphericity assumption).

Model predictions. Details about the computations leading to the model predictions are provided in the appendix. Predictions for encoding + mental rotation were obtained with the procedure described in the introduction, in which response times in the IM condition are used for estimating the encoding time and the difference between IM and CM conditions to obtain an estimate of the mental rotation time, which are then added to obtain the 'CM - 1 rotated' and 'CM - 2 rotated' predicted response times, shown in Figure 3B. For the NM conditions, we considered several versions. In one version, all stimuli are encoded and two stimuli are rotated (to ensure that when rotated they did not match the other patterns). In another version, all stimuli are encoded and only one is rotated, reflecting some form of self-terminating search. In the third version only two stimuli are encoded and one is rotated (self-terminating search). The second version proved to yield the best predictions, and therefore the results of this version are shown in Figure 3E.

The predictions for the memory search model take into account the different orders in which the three stimuli can be considered. The predicted response times are then formed by the weighted average of the search times associated with each of these orders (as outlined in the introduction). The resulting predicted response times are shown in Figures 3B and 3E, suggesting a larger slope for the 'CM - 1 rotated' than for the IM condition and a larger slope for the 'CM - 2 rotated' compared to the 'CM - 1 rotated' condition.

We also considered whether extra time needed to be assumed for the non-match condition, in which most of the participants were likely to respond with their dominant hand. The data did not suggest that such an assumption was required (adding extra time made the predictions worse), and therefore no additional time was added to either model.

2.2 Results

Figure 3C plots the average response times for the identity match (IM) and congruency match (CM) conditions (both conditions required an 'all the same' response from the participants), showing longer response times for larger values of the ESS and larger numbers of orientational alternatives. A similar pattern of results was found for accuracy (Figure 3D), precluding a speed-accuracy trade-off explanation for the response times. To examine the pattern of results in the response times statistically, we first considered the $ESS = 4$ and ESS=8 conditions separately in a 2 by 3 factorial design. A two-factor ANOVA with factors ESS ($ESS = 4$ and $ESS = 8$) and Orientation (IM, CM-1 rotated, CM-2 rotated) demonstrated significant main effects of the ESS ($F(1,18)=12.61$, $p=0.002$, partial $\eta^2=0.41$) and orientation ($F(1.3,23.8)=13.41$, $p=0.001$, partial $\eta^2=0.43$). Contrary to predictions of the memory search model (Figure 3B, left), but in line with encoding + mental rotation (Figure 3B, right), the interaction effect between the two factors was not significant ($F<1$). Posthoc tests (two by two repeated measures ANOVAs) revealed significant differences between the IM and CM 1-rotated conditions (main effect of Orientation: $F(1,18)=9.00$, $p=0.008$, partial $\eta^2=0.33$) and between the CM-1 and CM-2 rotated conditions (main effect of Orientation: $F(1,18)=8.07$, $p=0.011$, partial

η^2=0.31). A comparison between the IM conditions ($ESS = 1$, $ESS = 4$ and $ESS = 8$) revealed a significant effect of ESS (F(1.5,30)=10.8, p=0.001, partial η^2=0.38). The linear contrast reached significance (F(1,18)=13.8, p=0.002, partial η^2=0.43), but the quadratic contrast did not (F(1,18)=1.94, p=0.18, partial η^2=0.097), suggestive of a linear increase of response times with ESS.

Error rates for the IM and CM conditions show the same pattern of results as the response times, except for the ESS=8 IM condition (Figure 3D), which seems to have a lower than expected error rate. Higher error rates were found for combinations with more orientational alternatives (F(2,36)=8.64, p=0.001, partial η^2=0.32) and for larger ESS values (F(1,18)= 4.23, p=0.054, partial η^2=0.19). The interaction between ESS and Orientation did not reach significance (F(1.46, 26.24)=2.91, p=0.086, partial η^2=0.14).

Response times for the different NM conditions are shown in Figure 3E as (red) triangles. A general trend towards longer response times for stimuli with higher ESSs (F(1.75, 31.55)=10.16, p=0.001, partial η^2=0.36) can be observed, in agreement with predictions from the memory search model (R^2=95%), based on the best fitting regression line for the number of search steps (Figure 3E, squares), and slightly less so for the encoding plus mental rotation model (R^2=92%; circles). Akin to response times, error rates increased with larger summed ESS values across the stimuli presented on each trial (Figure 3F; repeated measures ANOVA: F(7,126)= 14.79, p<0.001, partial η^2=0.45).

2.3 Discussion

In Experiment 1, we sought to test the memory and encoding plus mental rotation models using three rather than two dot patterns in each comparison in a categorical same-different task. In the conditions requiring an 'all the same' response (IM, CM-1 rotated and CM-2 rotated), the data were consistent with an encoding plus mental rotation model and at odds with the memory search model. In contrast, the non-match conditions revealed response times more in line with the memory search model than the encoding plus mental rotation model.

The pattern of results for the three pattern IM and CM conditions are at odds with those found for two patterns (Lachmann and Geissler, 2002), where a significant interaction was found between the equivalence set size (ESS) and the relative orientation of the patterns (IM versus CM). One possible reason for the difference in the pattern of results for Experiment 1 and earlier studies could be that in the non-match (NM) condition we always used three different patterns. This may have led participants to adopting a strategy of initially examine two patterns and when these were different, to immediately produce a response without looking at the third pattern. Likewise, participants having seen two identical patterns may have immediately responded that all three patterns were identical. A second possible reason could be the use of simultaneously presented stimuli in Experiment 1, whereas earlier studies used a sequential presentation. Scanning and memory search strategies may be different if the stimuli are presented simultaneously on the screen. During simultaneous presentation participants may choose in which order they consider the stimuli, while in sequential presentation the order of processing of the stimuli is controlled by the experimenter. We examined the contributions of these two factors in Experiment 2 by including non-match trials with two identical patterns and by including a sequential presentation condition.

3 Experiment 2

In Experiment 2, we included three different types of stimulus combinations in the non-match (NM) condition. We either used three different patterns, two patterns that were identical in shape but different in orientation, together with a different pattern, or we used two patterns identical in shape and orientation together with a different pattern. All three combinations required a 'different' response. In addition, participants performed two blocks: One in which the stimuli were presented simultaneously and one with a sequential presentation, similar to that used in earlier studies (Lachmann and Geissler, 2002; Lachmann and van Leeuwen, 2005a,b). In order to keep the total testing time restricted, we reduced the overall frequency of the different types of trials with respect to Experiment 1, but kept the relative frequency of the ESS combinations and IM, CM, and NM trials intact.

3.1 Methods

Participants and apparatus. Twenty students (14 female, 6 male, aged between 18 and 25 years) from the University of Aberdeen participated in Experiment 2 in return for course credit. A dual-core PC running the OpenSesame software package (Mathôt et al, 2012) presented the stimuli on a 19 inch LCD screen and responses were collected using a standard keyboard.

Stimuli. Dot patterns identical to those of Experiment 1 were used. Participants completed 30 IM trials, 40 CM trials and 72 NM trials. IM trials had 10 trials of each ESS. Half of the CM trials had one stimulus rotated with respect to the other two stimuli ('1 rotated'), and in the other half three identical stimuli in different orientations were presented ('2 rotated'). NM trials consisted of 20 'NM-IM' trials in which two stimuli were identical and presented in the same orientation (the third stimulus was different), 12 'NM-CM' trials in which two stimuli were identical but presented in a different orientation, and 40 trials in which all three patterns were different (using combinations of $ESS = 1$, $ESS = 4$, and $ESS = 8$ stimuli in equal frequencies).

Design. Participants performed the 142 trials twice, the first time with a simultaneous presentation and the second time with the stimuli presented sequentially (blocks presented in the same order for all participants). The stimulus sequence for the simultaneous presentation was identical to Experiment 1, as illustrated in Figure 4A. During the sequential presentation, each stimulus was shown for 250ms interleaved by blank interstimulus intervals (ISIs) of 500ms (Lachmann and Geissler, 2002) (see Figure 4A). In the sequential condition, the top stimulus was presented first, followed by the bottom left and the bottom right stimulus. Responses were recorded from onset of the second stimulus. For each participant and each block (simultaneous and sequential) individual stimuli from each ESS category were selected at random (see Experiment 1 for the rationale and details about this procedure). Feedback about the accuracy of each trial was provided, as well as feedback about average response time and accuracy during each of the three breaks in each block. Participants required about 25 to 30 minutes to complete the experiment.

Data analysis and model predictions. None of the participants had error rates larger than 25% (mean error rate of 8%) in the IM and NM conditions and therefore all participants were kept in the analysis. As for Experiment 1, average response times were computed for each participant and condition separately before pooling them into a mean across participants. Before computing response times, error responses and response times longer than the mean plus 2 times the standard deviation or shorter than the mean minus 2 times the standard deviation were removed. Details about the model predictions are provided in the appendix. The model predictions for Experiment 2 include predicted response times for the non-match trials in which it is assumed that participants only consider the first two stimuli before responding (which we will refer to as 'self-terminating' in the data plots), as opposed to the 'exhaustive' search or encoding when all three stimuli are processed before a response is generatd.

3.2 Results

Response times for the simultaneous IM and CM conditions (Figure 4B) show an pattern identical to that observed in Experiment 1, providing evidence for the encoding plus rotation model, and against the memory search model. Since in Experiment 2, participants needed to consider all stimuli in order to generate a correct response, this result suggests that participants in Experiment 1 considered all three patterns before responding. A repeated measures ANOVA examining the effects of ESS and Orientation showed a significant main effect of ESS (comparing $ESS = 4$ and $ESS = 8$; $F(1,19)=26.68$, $p<0.001$, partial $\eta^2=0.60$), a significant main effect of Orientation (IM versus CM-1 and CM-2; $F(2,38)=23.64$, $p<0.001$, partial $\eta^2=0.55$), and no interaction between the two factors ($F< 1$). Posthoc tests show a significant difference between the IM and 'CM-1 rotated' conditions ($F(1,19)=45.19$, $p<0.001$, partial $\eta^2=0.70$), but not between the 'CM-1 rotated' and 'CM-2 rotated' conditions (F(1,19)=1.84, p=0.19, partial η^2=0.088). A comparison of the three ESS levels of the IM condition shows a significant effect of ESS (F(1.8, 34.2)=43.90, p<0.001, partial η^2=0.70). The linear (F(1,19)=61.10, p<0.001, partial η^2=0.76) and quadratic (F(1,19)=9.40, p=0.006, partial η^2=0.33) contrasts were both significant, suggesting an increasing effect of ESS. The error rates of the simultaneous condition show a similar pattern, with main effects of ESS (F(1,12)=13.17, p=0.002, partial η^2=0.41) and Orientation (F(2,38)=10.64, p<0.001, partial η^2=0.36), but no interaction between these factors (F<1). The only observation in the error rates not matching the response times seems to be the $ESS = 1$ IM condition. When comparing the three ESS levels (1, 4, and 8) for the IM condition, no significant effect on error rates is found (F<1).

Compared to the simultaneous condition, response times in the sequential condition (Figure 4C) show a slightly different pattern of results. While there was no three-way interaction between ESS, Orientation, and Stimulus timing (simultaneous versus sequential; F<1), there were significant interactions between Stimulus timing and ESS (F(2,38)=36.15, p<0.001, partial η^2=0.66) and Stimulus timing and Orientation (F(2,38)= 13.20, p<0.001, partial η^2=0.41). Within the sequential presentation condition, no effect of ESS was found (F(1,19)=1.18, p=0.29, partial η^2=0.059), but the effect of Orientation was significant (F(2,38)=3.43, p=0.043, partial η^2=0.15), without a significant interaction between ESS and Orientation (F< 1). Posthoc analyses showed a significant difference between the sequential IM and 'CM-1 rotated' (F(1,19)=4.46, p=0.048, partial η^2=0.19) but not between the 'CM-1 rotated' and 'CM-2 rotated' conditions (F<1). As for the simultaneous condition, the error rates in the sequential condition show a similar pattern to the response times (Figure 4), except that no significant effect of Orientation was found (F<1). In agreement with Experiment 1, the effect of ESS (F<1) on error rates and the interaction (F<1) were not significant.

Because of the inclusion of the IM and CM pairs in the NM trials, a large set of combinations is obtained, of which the results are shown in Figure 5. Response times in the simultaneous condition in Figure 5A replicate the NM condition of Experiment 1. A repeated measures ANOVA comparing response times across the different conditions shows a significant linear trend for response times to increase with increasing sums of ESS values of the patterns presented (F(1,19)=19.55, p<0.001, partial η^2=0.51). Further contrasts examining higher order components in this trend were not significant. The pattern of results for the sequential condition clearly deviates from this pattern. Instead, response times increase as a function of the combined value of the ESS until the 4-4-4 combination, after which a renewed increase starts. In contrast, error rates across the simultaneous and sequential condition are similar, although larger error rates are found in the sequential condition (F(1,19)= 6.47, p=0.020, partial η^2=0.26), in addition to longer response times for higher ESS combinations (F(8,152)= 35.85, p<0.001, partial η^2=0.65). The non-significance of the interaction between the ESS and the Stimulus timing

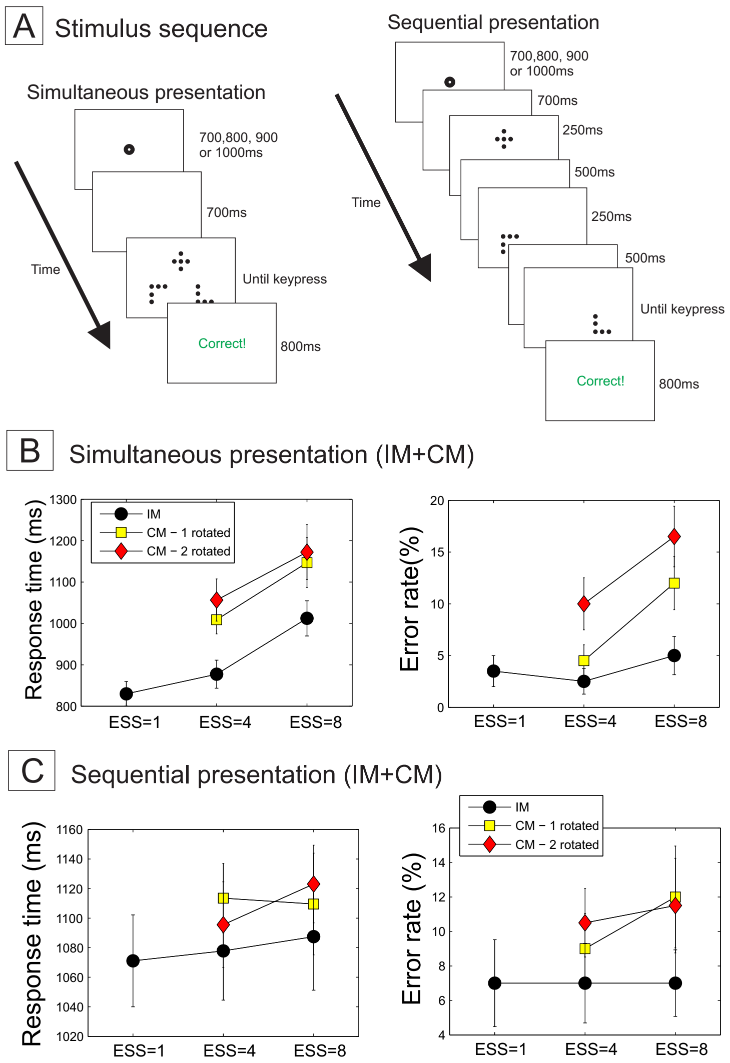

Fig. 4 Stimulus sequence, and IM and CM response times and error rates in Experiment 2. [A] Stimulus sequence for the simultaneous and sequential conditions (for details, see text). [B] IM and CM response times and error rates for the simultaneous stimulus presentation condition. [C] IM and CM response times and error rates for sequential presentation. Error bars in the different plots show the standard error of the mean.

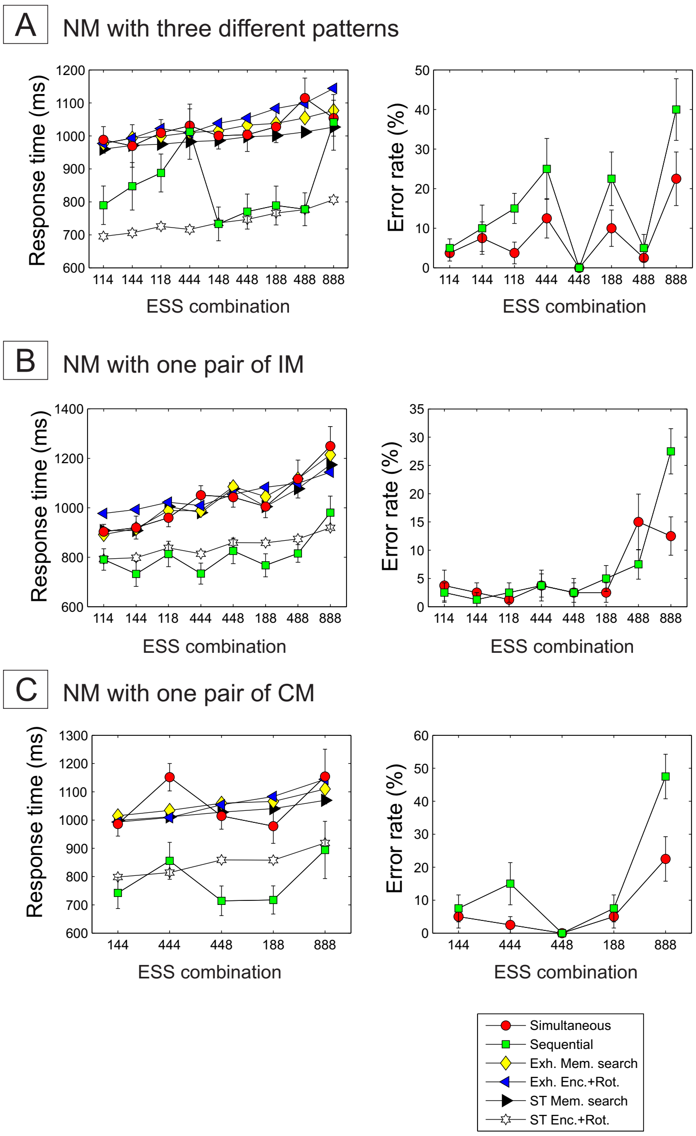

Fig. 5 Response times and error rates in the different NM conditions of Experiment 2. [A] NM response times and error rates for trials in which all three stimuli were different in shape. [B] NM response times and error rates for trials in which two stimuli were identical in shape and orientation (IM), while the third one was different in shape. [C] NM response times and error rates for trials with two patterns of the same shape but with a different orientation (CM) and pattern of a different shape. Diamonds, leftward and rightward triangles and stars show predictions from exhaustive (Exh.) and self-terminating (ST) search and encoding+rotation models. Note that for ease of comparison, the symbols of the different ESS conditions have been connected.

indicates that the pattern of error rates did not differ for sequential and simultaneous presentations ($F(8,152)=1.46$, $p=0.18$, partial $\eta^2=0.071$).

For NM trials containing an IM combination (Figure 5B) significantly faster response times were found for the sequential presentation condition ($F(1,19)= 36.48$, $p<0.001$, partial $\eta^2=0.66$) than for simultaneous presentation. This effect was complemented by a main effect of the ESS combination ($F(3.62, 68.79)=12.77$, $p<0.001$, partial $\eta^2=0.40$). Furthermore, the interaction between these two factors was significant ($F(7,133)= 2.28$, $p=0.032$, partial $\eta^2=0.11$). Posthoc tests showed significant differences between simultaneous and sequential presentations for almost all ESS combinations (p-values<0.011 for all but the 1-1-4 combination, $p=0.041$). The effect of ESS was also significant for both simultaneous and sequential presentations (p-values<0.01). Error rates did not differ across simultaneous and sequential presentations ($F<1$). They were, however, affected by the ESS combination ($F(3.31, 62.86)=14.46$, $p<0.001$, partial $\eta^2=0.43$). Furthermore, a significant interaction between the two factors was found ($F(3.59, 68.29)=2.97$, $p=0.03$, partial $\eta^2=0.14$). Pairwise comparisons between simultaneous and sequential presentations showed that this interaction was due to the ESS =8-8-8 combination, for which a significant difference in error rates was found ($t(19)=2.85$, $p=0.01$), whereas for the other combinations, the difference in error rates between presentation conditions was not significant.

For the NM triplets containing a CM combination (Figure 5C), response times for sequential presentation were faster than for simultaneous presentation ($F(1,19)=93.00$, $p<0.001$, partial $\eta^2=0.83$), and a main effect of the ESS ($F(4,76)= 4.71$, $p=0.002$, partial $\eta^2=0.20$) was found, but the absence of an interaction between ESS and Stimulus timing ($F<1$) indicated that the pattern of results was the same for the different presentation modes. Error rates showed a similar pattern of results with a significant difference between simultaneous and sequential presentation ($F(1,19)=5.66$, $p=0.028$, partial $\eta^2=0.23$) and a significant main effect of the combined ESS ($F(2.59, 49.17)= 23.05$, $p<0.001$, partial $\eta^2=0.55$), but no interaction between the two factors ($F(2.80, 53.13)= 2.64$, $p=0.063$, partial $\eta^2=0.12$).

3.3 Discussion

Experiment 2 replicated most of the results of Experiment 1, suggesting that participants in Experiment 1 considered all three stimuli before responding when stimuli are presented simultaneously. A different pattern for sequentially presented stimuli was found, suggesting that participants may adopt a different response strategy depending the stimulus timing (simultaneous versus sequential presentation).

By comparing the response times to those predicted by a memory search model (Lachmann and Geissler, 2002) and an encoding plus mental rotation strategy, we aimed to determine the mechanism best explaining the observed pattern of results. A comparison of the simultaneous response time data from the IM and CM conditions (Figure 4) with the predicted patterns (Figure 3B) provides evidence for a model based on the combination of encoding plus mental rotation. The best data fit, however, was obtained when only one, rather than two stimuli were rotated before reaching a decision. The latter assumption may not hold for trials in which the two identical stimuli were considered first (on average, one third of the trials). Furthermore, the sequential IM and CM data lack an effect of ESS, which was not predicted by either the memory search or the encoding plus mental rotation model. The pattern of the response times for the simultaneous NM conditions (Figure 5) was well approximated by both the memory search and the encoding+mental rotation model assuming that all three patterns are processed before a decision is made ('exhaustive search or encoding'). The sequential presentation conditions seem to suggest a self-terminating encoding+mental rotation model (ST; Figure 5). While it appears that there is little difference between the exhaustive and self-terminating response times of the memory model, closer inspection of the predictions shows that there is an advantage for self-terminating search, but that the linear regression mapping search steps to response times was not sufficiently strong to explain the large differences between simultaneous and sequential search times. Note that because the self-terminating and exhaustive predictions differ, there is no need to rely on other measures such as the variance in the data to distinguish between self-terminating and exhaustive search (Van Zandt and Townsend, 1993).

The sequential condition shows a pattern of results that deviates from the predictions of both the memory search model and the encoding plus rotation account. This condition also shows large variability in response times across participants, which suggests that participants used different strategies to perform the task. Because the data do not fit either model, it may be suspected that additional strategies have been used, as a mixture of the two accounts would have resulted in increase in response times with ESS, contrary to what was observed. We will return to this issue in the General Discussion, where we will discuss possible alternative models for future consideration.

The results for the sequential condition are unexpected, and one may therefore wonder whether they were the consequence of the use of three patterns rather than two, or whether other specifics about our experimental setup, such as the way the dots patterns were presented (as black dots on a white background), the responses was collected (using a standard keyboard), and the amount of practice participants received (only 16 trials in our experiments), were causing the unexpected pattern of results. We therefore replicated the original experiment (Lachmann and Geissler, 2002), using our setup of Experiments 1 and 2. To examine the influence of the timing of the stimuli, we asked each participant to complete one simultaneous and one sequential presentation block.

4 Experiment 3

Experiment 3 replicated the two-pattern experiment by Lachmann and Geissler (2002) using the experimental setup used in Experiments 1 and 2. In addition, Experiment 3 examined the difference between sequential and simultaneous presentation of the stimuli when only two stimuli are presented on each trial.

4.1 Methods

Twenty-one participants (14 female, 9 male) remained for the data analysis (after two participants were removed for producing more than 25% incorrect responses in the IM and CM conditions). Participants all took part voluntarily without receiving reimbursement for their participation. They performed two blocks of trials in which two dot patterns were either presented sequentially or simultaneously. The order of the presentation modes (sequential versus simultaneous) was randomized across participants (resulting in 12 participants starting with the simultaneous and 9 with the sequential presentation). Each block contained 135 trials, preceded by 10 practice trials. The distribution of the conditions followed that used in Lachmann and Geissler (2002), with 8 IM-ESS=1, 16 IM-ESS=4, 14 IM-ESS=8, 16 CM-ESS=4, and 14 CM-ESS=8 trials that required a 'same' response and 67 NM trials requiring a 'different' response (14 ESS4-4, 10 ESS8-8, 8 ESS1-4, 7 ESS1-8, and 28 ESS4-8 trials), reducing the original number of trials by half. As before, stimuli were randomly selected for each ESS on every trial. The same equipment was used as in Experiments 1 and 2, including the stimulus software package Opensesame (Mathôt et al, 2012) to present the stimuli. In the simultaneous presentation condition, two dot patterns were presented 10 degrees left and right of fixation and remained on the screen until participants gave their response. In the sequential presentation condition, the first stimulus was shown on the left for 250ms, followed by a blank screen (500ms) and the second stimulus on the right until key-press.

4.2 Results

An overview of the results of Experiment 3 is provided in Figure 6. In contrast to the three-pattern design in Experiment 2, the two-pattern simultaneous and sequential conditions of Experiment 3 show a very similar pattern of results. This similarity was confirmed in a three-factor repeated measured ANOVA, testing the effects of Stimulus timing (sequential or simultaneous), ESS (4 or 8) and Orientation (IM versus CM), showing a non-significant three-way interaction between the three factors (F(1,20)=2.0, p=0.17, partial η^2=0.092). Consistent with Lachmann and Geissler (2002) and predictions of a memory search model (Figure 2A), a significant two-way interaction was found between ESS and Orientation (F(1,20)=7.85, p=0.011, partial η^2=0.28). Furthermore, the interaction between ESS and Stimulus timing was significant ($F(1,20)= 8.62$, $p=0.008$, partial $\eta^2=0.30$). Finally, significant main effects of Stimulus timing ($F(1,2)=20.29$, $p<0.001$, partial $\eta^2=0.50$), ESS ($F(1,20)=18.70$, $p<0.001$, partial $\eta^2=0.48$) and Orientation ($F(1,20)=24.16$, $p<0.001$, partial $\eta^2=0.55$) were found. For non-match (NM) trials, a repeated measures ANOVA revealed significant main effects of the Stimulus timing ($F(1,20)=17.87$, $p<0.001$, partial $\eta^2=0.47$) and ESS ($F(1.45, 29.08)=22.54$, $p<0.001$, partial $\eta^2=0.53$). No significant interaction was obtained ($F<1$).

Error rates in the IM and CM conditions (Figure 6A) showed a similar pattern to the response times, with the exception that the three-way interaction between ESS, Orientation and Stimulus timing reached significance ($F(1,20)=7.03$, $p=0.015$), possibly reflected by the steeper slope of the CM condition for the simultaneous presentation. Error rates for the non-match condition revealed an effect of ESS ($F(3,60)=75.9$, $p<0.001$, partial $\eta^2=0.79$), but no effect of stimulus timing ($F<1$) or an interaction between these factors ($F(3,60)=1.83$, $p=0.15$, partial $\eta^2=0.084$).

4.3 Discussion

In Experiment 3, we replicated the original paradigm by Lachmann and Geissler (2002) using the setup used in Experiments 1 and 2. An identical pattern of results was found (compare Figures 2 and 6) with an interaction between the ESS and the IM/CM distinction, in agreement with the memory search model (Lachmann and Geissler, 2002) and at odds with an explanation based on encoding and mental rotation (Figure 2). Moreover, the interaction between the two factors was also found for the simultaneous presentation (Figure 6). These findings suggest that the non-significant interaction between ESS and stimulus rotation was specific for conditions using three rather than two dot patterns (Experiments 1 and 2). It also means that the exact conditions under which the experiments were performed (e.g., type of dots, response collection) were not crucial for obtaining the effects. This includes the use of randomly selected stimuli within each ESS category on each trial.

The non-match conditions of Experiment 3 show a slightly different pattern from that obtained by Lachmann and Geissler (2002). Standard errors in this condition are large, so the slight differences in these conditions may be due to the restricted amount of practice of our participants and the reduced number of trials with respect to the study by Lachmann and Geissler (2002). The effects of practice are also visible in the overall response times, which were lower in the Lachmann and Geissler (2002) study than in our data (sequential condition).

5 General Discussion

In three experiments, we examined the influence of the Goodness of Garner dot patterns (as measured in their equivalence set size, ESS) and their spa-

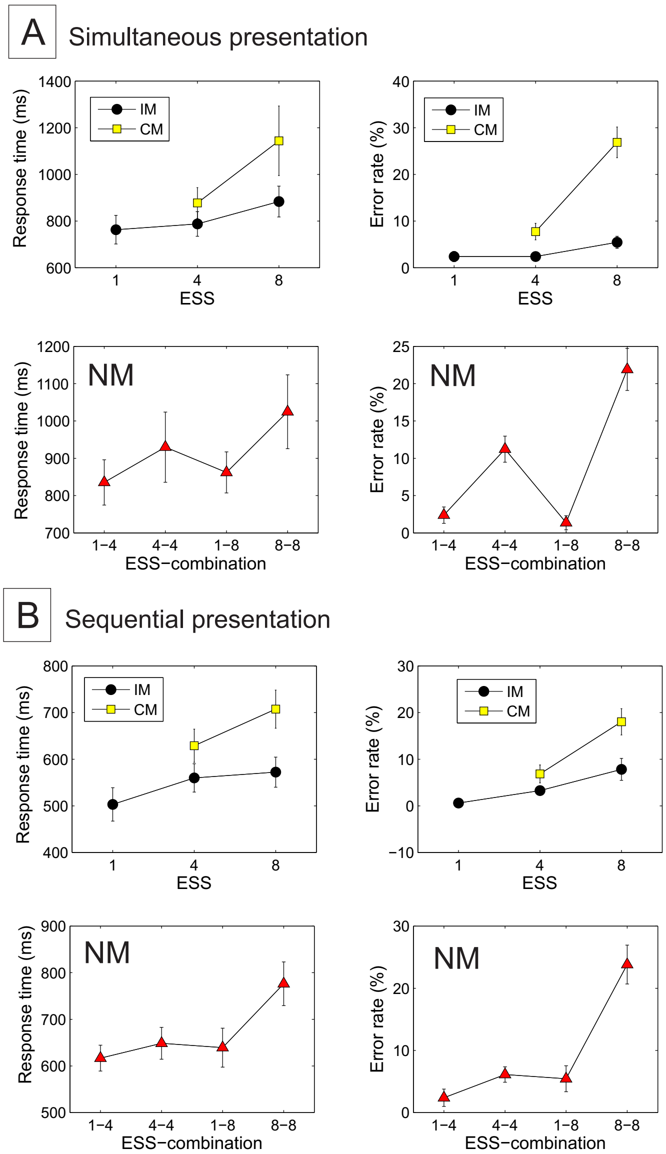

Fig. 6 Results of Experiment 3 in which participants were asked to compare two dot patterns. [A] Response times and error rates for the simultaneous presentation condition. [B] Response times and error rates for sequentially presented dot patterns.

tial orientation on response times in a categorical matching task. We carried out this investigation with the with the aim to distinguish between two possible explanations of the effects of these factors obtained previously (Lachmann and Geissler, 2002; Lachmann and van Leeuwen, 2005a,b). In accordance with the interaction between the two factors (Figure 2) in these earlier studies, a memory search model was proposed (Lachmann and Geissler, 2002), in which all possible orientations of a dot pattern are searched before reaching a decision. The memory search model was preferred over a model in which response times are determined by a stimulus encoding time, in combination with the time needed to mentally rotate the stimuli. However, by comparing predictions from the two accounts (Figure 2), we found that the same-different task for two dot patterns was not very specific in distinguishing between the two accounts.

For these reasons, we increased the number of stimuli in the task from two to three, resulting in a much large number of possible stimulus combinations, allowing for a more detailed test of the two accounts. Our experiments provide an extension and replication of prior studies with the same-different task. Experiment 1 extends existing studies by including three patterns. Experiment 2 examines the role of the presentation sequence for these three patterns. Experiment 3 examines the role of presentation sequences for two patterns. All experiments involve the same task, and apply the same stimuli. For these reasons, we set out by assuming the same underlying processes may be important in each of the experiments. Our data suggest this may not be the case. Response times on trials in which patterns were identical in shape (the IM and CM conditions) provided evidence against the memory search model and in favor of the encoding plus mental rotation model. The trials in which the patterns were not all of the same shape (NM trials) as well as our replication of the original Lachmann and Geissler (2002) two-pattern study favored the memory search model. Together, the data suggest that a combination of encoding plus mental rotation and memory search may be needed to explain all data.

5.1 Alternative models

The models considered so far assume that memory search or encoding plus mental rotation does not start until at least two of the dot patterns have been presented (sequential presentation) or inspected (simultaneous presentation). However, it may well be that memory search or encoding starts immediately after the first stimulus inspection.. Models that assume such cascaded processing of the stimuli are more complex than the two models considered here, but they would pose an interesting alternative, in particular because our experiment using three stimuli on each trial revealed differences between sequential and simultaneous presentations (Experiment 2). The construction of such models assuming cascaded processing is illustrated in Figure 7. This figure also illustrates the point that in both the simultaneous and sequential conditions, the stimuli are likely to be considered one by one, either due to the way they are presented (one by one), or by the requirement to either fixate (make an eye movement) or shift covert attention to each of the dot patterns for processing. The main difference is the rate at which the different stimuli are considered, which can be expected to be higher for the simultaneous than for the sequential presentation conditions (as fixations commonly last for around 200 to 300ms, whereas ISIs of 500ms were used for the sequential presentation condition, although it would be interesting to see what would happen if the ISI in the sequential presentation condition would be reduced).

Different versions of the cascaded model are possible. First, a distinction can be made between serial and parallel processing of the stimuli. In parallel processing, the encoding or memory search for the second stimulus can start as soon as this stimulus is inspected, without the need to wait until processing of the first stimulus is completed. Note that in its original form, the memory search model assumes serial processing, so that the search can start where the previous search has ended (Lachmann and Geissler, 2002). A second distinction is whether in non-match trials all three stimuli are considered, or whether processing terminates after two different dot patterns have been processed. Note that in Experiments 1 and 2 we have assumed that encoding occurs for all three stimuli, but rotation for one stimulus only. We have also compared the predictions of self-terminating encoding plus mental rotation and memory search models with the data of Experiment 2, suggesting that self-terminating encoding plus mental rotation may explain the data in the sequential presentation condition. Third, the models so far have assumed fixed processing durations, but one may also assume a random distribution of processing times, so that on one trial an $ESS = 1$ stimulus may take 100ms to process, whereas on the next trials the same $ESS = 1$ stimulus takes 120ms or 150ms. Random processing times would allow for the prediction of response time distributions, but would not be expected to influence average response times under serial processing[3].

To illustrate the increased complexity of the computations with respect to the models considered so far, assume one of the encoding plus rotation models applied to a three stimulus CM sequence with response times measured from the onset of the second stimulus. Also assume that processing of the next stimulus can only take place after processing of the previous stimulus has completed (serial processing). Response times will then depend on the assumed durations of encoding (different for the different ESSes) and rotation, as well as the durations of stimulus presentation and the intermediate blanks (for sequential presentations) or the durations of the attention or gaze shifts (for simultaneous presentations). Figure 8 illustrates this point by showing several possible timing sequences. For example, if encoding of the first stimulus takes less time than the stimulus presentation and blank screen, response times will not be affected by the first stimulus (Figure 8, Situation 1). If encoding of

[3] Under parallel processing, effects such as statistical facilitation may occur, if the response is determined by the process to complete first.

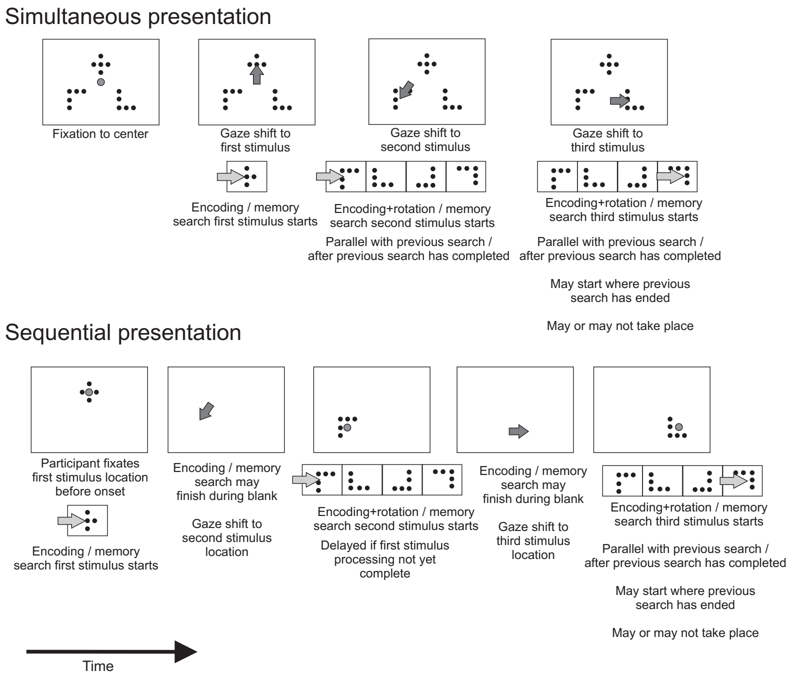

Fig. 7 Illustration of possible alternative mechanisms involved in the same-different task for three dot patterns across simultaneous and sequential presentations. In the sequential presentation condition, it is assumed that participants shift their attention or gaze to the expected stimulus location before onset, so that no additional time is needed for these shifts, whereas in the simultaneous presentation condition, shifts of attention or gaze are made. For more details, see the text.

the first stimulus takes more time, response times will include a component consisting of the difference of the stimulus presentation duration plus blank duration and the encoding time (Figure 8, Situation 2). If encoding of the second stimulus plus rotation takes less time than the stimulus presentation duration and the blank duration, then the encoding duration of the second stimulus enters the reaction time equation (Figure 8, Situation 3). Otherwise, the stimulus presentation plus blank duration is entered instead. The situation will become more complex when the duration of each processing stage is not assumed to be fixed, but is instead drawn from a random distribution. Given the multitude of possible alternative models, we leave the examination of the model predictions for these models for future work.

One possible test of cascaded models such as the ones proposed in Figure 7 would involve sequential presentation, in which presentation duration and interstimulus intervals (ISI) are varied. If cascaded models present a better representation of the data, the ESS of the first and second stimulus in the sequence would have a reduced influence. Varying the presentation duration and the ISIs would also allow to examine the role of encoding time and that of

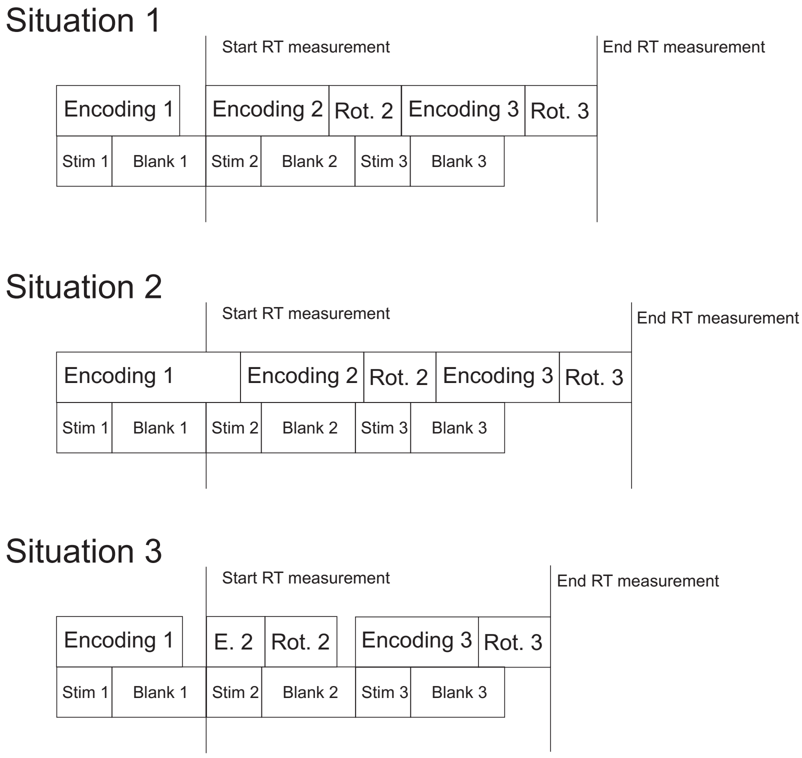

Fig. 8 Illustration of the computations involved in one version of an alternative model, showing three possible timing situations. Which situation takes place depends on the individual encoding durations for the three stimuli ('encoding') and rotation durations for the second and third stimulus ('rot'), as well as the stimulus presentation duration ('stim') and the blank duration ('blank').

memory load. One possible reason for the contrasting results in the three and two pattern sequences, is the difference in the overall stimulus presentation duration. This difference may have provided sufficient encoding time for the three pattern condition, but not for the two pattern condition. Varying the duration of the ISI would provide an indication whether this effect may have played a role. Another difference between three and two patterns is memory load. Storing items in memory for comparison may may involve a higher load for three than for two patterns. By reducing the ISI, the amount of time that the patterns need to be stored would be reduced, possibly leading to a pattern of results in the sequential condition more closely resembling that of the simultaneous condition.

5.2 Stimulus encoding versus memory search

Several previous studies using the Garner dot pattens (Garner and Clement, 1963) have attempted to distinguish between the influences of stimulus encoding and memory search (Bell and Handel, 1976; Checkosky and Whitlock, 1973; Clement and Varnadoe, 1967; Garner and Sutliff, 1974; Pomerantz, 1977; Sebrechts and Garner, 1981). One approach taken was to use the Sternberg (1969) methodology (the 'additive factor method') in which separate processes are assumed when two factors are shown to influence response times independently as demonstrated by a non-significant interaction in an analysis of variance. This means that by varying Goodness and one factor assumed to influence stimulus encoding (e.g., stimulus visibility) and another factor influencing memory search (e.g., the memory set), the factor that interacts with Goodness will indicate what cognitive process is linked to stimulus Goodness. This method was employed by Checkosky and Whitlock (1973) who presented participants with dot patterns which they had to compare to a memory set of either two or three items with two levels of Goodness ($ESS = 4$ and $ESS = 8$). In addition, the visibility of the patterns was varied between two levels (see also Lachmann and van Leeuwen (2007b)). Whereas a significant interaction was found between the number of items in memory and stimulus Goodness, no such interaction was observed between stimulus visibility and Goodness, leading the authors to conclude that Goodness influences memory search rather than stimulus encoding. Later, however, it was argued that while this method might suggest that Goodness does not influence encoding, it may well be that Goodness only influences part of the encoding process (Pomerantz, 1977). Furthermore, additional analysis of Checkosky and Whitlock (1973)'s data suggested that Goodness may influence stimulus encoding for at least part of the data (Garner, 1974).

A second approach is to present stimuli for a brief time, followed by a mask, and to ask participants to reproduce the briefly presented stimulus. If stimuli with high Goodness are reproduced more accurately than stimuli with lower Goodness, this would suggest that good stimuli are encoded more quickly than poor stimuli. This approach was taken by Bell and Handel (1976), who indeed found better reproduction accuracy for good patterns, and this difference between good and poor stimuli disappeared when no mask was used. This result was later criticized for possibly probing into different encoding requirements, as the task was reproduction rather than comparison (Pomerantz, 1977). Sebrechts and Garner (1981) seemed convinced by the evidence by Bell and Handel (1976), but suggested that the influence of Goodness on encoding is relatively small compared to that on memory.

A third approach is to manipulate the items to be kept in memory by assigning one response to a certain set of items and another response to either a different set, or 'anything else' (Pomerantz, 1977). The assumption is that participants keep the sets of items in memory, but only when the set is specified. If response times to a target stimulus are influenced by the Goodness and number of items in memory, this means that Goodness influences memory rather than encoding. Such effects were indeed found (Pomerantz, 1977), although also a small but significant effect of the Goodness of the displayed item was found.

A fourth approach is to use a same-different task, as in the experiments described here using a long interstimulus interval (ISI) between the two stimuli. Due to the long ISI, it may be assumed that encoding of the first stimulus is complete before the onset of the second stimulus, and should therefore not influence response times. This approach was taken by Sebrechts and Garner (1981) who found faster response times when both the first and the second stimulus were good than when both stimuli were poor. For unequal stimuli ('non-match' in our experiments), the second stimulus Goodness only marginally influenced response times, whereas the Goodness of the first stimulus had a strong influence, leading to the conclusion that memory, but not encoding is influenced by Goodness.

A fifth approach is to examine the nature of encoding, rotation and memory search tasks by examining whether processing interferes with a secondary task in a dual task setting. This approach suggested that encoding is a peripheral process, whereas memory search and mental rotation are central (Carrier and Pashler, 1995; Ruthruff et al, 1995). By showing that the same-different task was central, it was suggested that memory search rather than encoding was involved in the Goodness effects (Lachmann and van Leeuwen, 2007a,b, 2008).

These earlier studies, with exception for the latter one, have the limitation that they used only two levels of Goodness (good versus poor), which limits the number of conditions to be explained by a possible model. Moreover, whereas the studies generated predictions about the ordering of the conditions in terms of response times, no exact predictions were provided. We here use three categories (based on the equivalence set size) and predict response times for each stimulus condition. By doing so, we obtain a stronger test of the mechanisms underlying the effects of Goodness. Our results are in line with the previous results in that they suggest that both mechanisms are at work.

Note that there may be a difference in the memory processes assumed in these earlier studies and the memory search modeled here and in Lachmann and Geissler (2002). In the earlier studies, memory involved maintaining the stimuli associated with a response, whereas here, memory search involves the search of the equivalence set that automatically emerges when a stimulus is shown. This involvement of this latter type of memory search is supported by the findings in the simultaneous presentation conditions in our experiments. In these condition, stimuli are continuously available to the participants and therefore no item has to be kept in memory, strongly reducing the need for a search of response alternatives.

5.3 Task and context effects

In our experiments and simulations, we have focused on the categorical matching task, in which participants have to decide whether two stimuli are identical regardless of their orientation, and on designs with roughly equal numbers of the different ESS combinations. These two factors (task and design), however, have been shown to influence response times (Lachmann and van Leeuwen, 2005a,b) and should therefore be considered when trying to decide between different explanations of the effects of ESS and stimulus orientation. For the alternative task, in which participants are asked to only indicate that the patterns match when they also have the same orientation (a physical same-different task), the models make the following predictions. The encoding plus mental rotation model predicts that response times depend on the ESS in the IM and CM conditions, but that there will be no difference between IM and CM trials (as no mental rotation is required to reach a decision). This latter prediction is at odds with observations, showing faster response times for IM than for CM trials (Lachmann and van Leeuwen, 2005b). The memory search model, in contrast, predicts a difference between IM and CM trials, reflecting an automatic tendency to 'perceive' patterns within their categories.

It not perfectly clear how the different models explain the effect of the proportion of the different stimulus combinations (Lachmann and van Leeuwen, 2005a). Possibly repeated encounters of one type of stimulus reduces the time required for encoding, which more strongly influences response times to stimuli that are shown often. In addition, the need to rotate stimuli often may lead to faster rotating of stimuli on successive trials. This explanation, however, does not explain why the frequency of individual patterns does not influence response times, whereas the occurrence of an ESS does (Lachmann and van Leeuwen, 2005a). One possibility is that an increased frequency of a certain stimulus category creates a response bias, which would operate at an ESS level rather than a stimulus level. The memory search model explains the effects of the relative frequencies by different slopes of the function linking the number of search steps to the response times, suggesting that processing certain ESS categories becomes faster or slower, depending on their relative frequency in the experiment.

5.4 ESS effects

As in earlier studies (Lachmann and Geissler, 2002; Lachmann and van Leeuwen, 2005a,b, 2010), we find strong effects of the equivalence set size (ESS) across almost all conditions, providing further evidence for the role of the equivalence set size based on rotation and reflection (R&R) transformations as proposed, for example, by Garner (1970). In our experiments, we based our design on the ESS rather than on individual patterns. The fact that we replicate the original findings by Lachmann and Geissler (2002) in our Experiment 3 shows that, indeed, the ESS is the critical factor influencing same-different response times rather than aspects of individual patterns. Future experiments can therefore adopt a strategy in which members from a certain ESS are randomly selected for each trial, allowing for reduced testing times compared to when each possible combination of the individual patterns need to be tested.

ESS effects have been found across a range of tasks and dependent measures. For example, ESS has been shown to influence visual search, where a target embedded in differently oriented versions of the target required longer search times for high ESS than for low ESS targets (and distractors) (Rauschenberger and Yantis, 2006). ESS has also been shown to influence ERP components both in a physical and a categorical same-different task (Berti et al, 2000; Berti and Roeber, 2013, in press). Further effects of ESS were found on repetition blindness in a rapid serial visual presentation paradigm (RSVP). Repetition blindness was more prominent for high ESS patterns when the two stimulus were presented at a shorter interval (<500ms), whereas the reverse effect was found for longer inter-stimulus intervals (>500ms) (Takahashi et al, 2013).

5.5 Conclusion

In three experiments we examined the underlying processes involved in the effects of stimulus Goodness in a categorical same-different task by varying the number of stimuli and the presentation timing (simultaneous versus sequential presentation). The observed response times were compared with predictions from a memory search model (Lachmann and Geissler, 2002) and those from an account based on stimulus encoding plus mental rotation. Neither account could fully account for our data, suggesting, in line with earlier results, that these models should be reconfigured in terms of cascaded processing. In summary, and in combination with the previous studies (Lachmann and Geissler, 2002; Lachmann and van Leeuwen, 2005a,b), it can be maintained, however, that effects of Goodness depend strongly on the specific conditions of the task, but that a central component of representational economy (here exemplified by ESS) remains universally present across all task variations.

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6 Appendix

6.1 Experiment 1 model predictions

Encoding plus mental rotation. Let $\mathcal{E}_1$, $\mathcal{E}_2$, and $\mathcal{E}_3$ be the time needed for encoding the first, second and third stimulus on any given trial. Furthermore, let $\mathcal{M}$ be the time needed for mental rotation. Responses in the IM do not require mental rotation, and therefore response times will be equal to:

$$\mathrm{RT}_{\mathrm{IM}} = \mathcal{E}_1 + \mathcal{E}_2 + \mathcal{E}_3$$

If the three stimuli are the same in shape (as is the case in the IM condition), this equation will reduce to:

$$\mathrm{RT}_{\mathrm{IM}} = 3 \cdot \mathcal{E}$$

with $\mathcal{E}$ the encoding time of the identical shape.

In the CM and NM conditions mental rotation is required. For CM trials with one differently oriented stimulus, one mental rotation step is needed, resulting in response times equal to:

$$\mathrm{RT}_{\text{CM-1}} = 3 \cdot \mathcal{E} + \mathcal{M}$$

With two differently oriented stimuli, two mental rotation steps are needed:

$$\mathrm{RT}_{\text{CM-2}} = 3 \cdot \mathcal{E} + 2 \cdot \mathcal{M}$$

While theoretically, it may be expected that two mental rotation steps are needed to ascertain that the second and third stimulus in the non-match (NM) condition are not rotated versions of the first stimulus, the data suggest that only one rotation step is required, and therefore response times in this condition are predicted to be:

$$\mathrm{RT}_{\mathrm{NM}} = \mathcal{E}_1 + \mathcal{E}_2 + \mathcal{E}_3 + \mathcal{M}$$

For our predictions of $\mathcal{E}_1$, $\mathcal{E}_2$, and $\mathcal{E}_3$, we used the average response times in the IM conditions. For example, if the first stimulus is from the $ESS = 4$ category, $\mathcal{E}_1$ is set to the average IM response time for $ESS = 4$. We chose to estimate $\mathcal{M}$ from the difference in the response times in the IM $ESS = 4$ and the CM-1 rotated $ESS = 4$ response times, but as discussed earlier, alternative options are to use a combination of the $ESS = 4$ and $ESS = 8$ categories or to also take NM averages into account.

Memory search Predictions for the memory search model are based on the size of the ESS, which varies between 1, 4 and 8. In the IM condition, the array needs to be searched only once, because for each new stimulus, the search jumps to the same stimulus in the array. The expected number of search steps is therefore equal to:

$$S_{\text{IM}} = \frac{\text{ESS} + 1}{2}$$

with ESS the size of the equivalence set of the stimulus. Predictions for the CM conditions depend on the number of differently oriented items and the order in which the stimuli are inspected. Let ESS_1 be the ESS of the stimulus whose orientation occurs twice and ESS_2 the ESS of the stimulus occurring once. The different possible orders in which the stimuli can be inspected are: $\text{ESS}_1 - \text{ESS}_1 - \text{ESS}_2$, $\text{ESS}_2 - \text{ESS}_1 - \text{ESS}_1$, $\text{ESS}_1 - \text{ESS}_2 - \text{ESS}_1$, which due to randomization of the stimulus positions are expected to occur in equal frequencies. The $\text{ESS}_1 - \text{ESS}_1 - \text{ESS}_2$ and $\text{ESS}_2 - \text{ESS}_1 - \text{ESS}_1$ sequences have one change between ESS_1 and ESS_2, whereas the sequence $\text{ESS}_1 - \text{ESS}_2 - \text{ESS}_1$ has two. The former two sequences require $(\text{ESS} + 1)$ search steps, whereas the latter sequence requires $\frac{3}{2}(\text{ESS} + 1)$ search steps, resulting in an overall predicted number of search steps equal to:

$$S_{\text{CM-1}} = \frac{1}{3} \cdot \frac{3}{2}(\text{ESS} + 1) + \frac{2}{3}(\text{ESS} + 1) = \frac{7}{6}(\text{ESS} + 1)$$

Trials with three differently oriented same shape stimuli involve two new searches and the predicted number of search steps is therefore equal to:

$$S_{\text{CM-2}} = \frac{3}{2}(\text{ESS} + 1)$$

In the non-match conditions the predicted number of search steps is:

$$S_{\text{NM}} = \frac{1}{2}(\text{ESS}_1 + 1) + \frac{1}{2}(\text{ESS}_2 + 1) + \frac{1}{2}(\text{ESS}_3 + 1) = \sum_{i=1}^{3} \text{ESS}_i + \frac{3}{2}$$

To convert steps to predicted response times, a first order polynomial least squares fit was used, for which an estimated intercept of 662.8 and slope of 29.2 was obtained.

6.2 Experiment 2 model predictions

Predicted response times for the IM, CM and NM with three different shapes are identical to Experiment 1. Predicted response times for the NM trials with one IM or CM pair for the encoding model are:

$$\text{RT}_{\text{NM-IM}} = 2 \cdot \mathcal{E}_1 + \mathcal{E}_2 + \mathcal{M}$$

assuming one general R&R step, with $\mathcal{E}_1$ the encoding time for the IM or CM stimulus and $\mathcal{E}_2$ that for the different shape.

Predicted numbers of search steps for the memory search model take into account the different orders in which the stimuli can be inspected. For the IM pair, there are three possible orders, similar to the CM - 1 rotated condition above, leading to the predicted number of steps equal to:

$$\mathrm{S}_{\text{NM-IM}} = \frac{2}{3}\left(\frac{\mathrm{ESS}_1 + \mathrm{ESS}_2}{2}\right) + \frac{1}{3}\left(\mathrm{ESS}_1 + \frac{ESS_2}{2}\right) + \frac{3}{2}$$

For the NM-CM condition, there are six possible orders, but the predicted number of search steps can be reduced to:

$$\mathrm{S}_{\text{NM-CM}} = \mathrm{ESS}_1 + \frac{\mathrm{ESS}_2}{2} + \frac{3}{2}$$

with ESS_1 the ESS of the pair (IM or CM) in the NM trial. As before, a first order polynomial least squares fit was used to convert the search steps to the predicted response times. In order to obtain a good data fit, different best fits were used for the three NM conditions, with similar slopes and intercepts for the NM and NM-CM data, but a different values for the NM-IM data.

For the self-terminating search, predicted response times or number of search steps of two of the stimuli were used, unless the two first two stimuli in the possible sequence were identical. The following predictions are obtained for the NM-IM trials:

$$\mathrm{RT}_{\text{NM-IM}} = \frac{2}{3}(\mathcal{E}_1 + \mathcal{E}_2) + \frac{1}{3}(2 \cdot \mathcal{E}_1 + \mathcal{E}_2) + \mathcal{M}$$

(for encoding).

$$\mathrm{S}_{\text{NM-IM}} = \frac{\mathrm{ESS}_1 + \mathrm{ESS}_2}{2} + 1$$

(for memory search).

For the NM-CM trials, the predictions are:

$$\mathrm{RT}_{\text{NM-CM}} = \frac{2}{3}(\mathcal{E}_1 + \mathcal{E}_2) + \frac{1}{3}(2 \cdot \mathcal{E}_1 + \mathcal{E}_2) + \mathcal{M}$$

(for encoding).

$$\mathrm{S}_{\text{NM-CM}} = \frac{2}{3}\left(\frac{\mathrm{ESS}_1 + \mathrm{ESS}_2}{2} + 1\right) + \frac{1}{3}\left(\frac{2\mathrm{ESS}_1 + \mathrm{ESS}_2}{2}\right)$$

(for memory search).

6.3 Experiment 3 model predictions

Experiment 3 used two stimuli, similar to Lachmann and Geissler (2002), and therefore the same predictions apply. For stimulus encoding plus mental rotation the predicted response times are equal to:

$$\mathrm{RT_{IM}} = 2 \cdot \mathcal{E}$$
$$\mathrm{RT_{CM}} = 2 \cdot \mathcal{E} + \mathcal{M}$$
$$\mathrm{RT_{NM}} = \mathcal{E}_1 + \mathcal{E}_2 + \mathcal{M}$$

with $\mathcal{E}$ the encoding duration for the identical pair of stimuli, and $\mathcal{E}_1$ and $\mathcal{E}_2$ the encoding times for the two different stimuli. The encoding times are estimated from the response times in the IM conditions. The rotation time ($\mathcal{M}$) was estimated using the difference between the response times in the $ESS = 4$ IM and CM conditions, although alternative methods are possible.

For the memory search model, the predicted number of search steps is equal to (Lachmann and Geissler, 2002):

$$\mathrm{S_{IM}} = \frac{(\mathrm{ESS} + 1)}{2}$$
$$\mathrm{S_{CM}} = (\mathrm{ESS} + 1)$$
$$\mathrm{S_{NM}} = \frac{(\mathrm{ESS}_1 + \mathrm{ESS}_2)}{2} + 1$$

Conversion to response times leading to the predictions in Figure 2 was based on a first order polynomial least squares fit of the IM, CM and NM data.