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Dynamic Instability of Visuospatial Images

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Five experiments using a visuospatial task were conducted to study memory accuracy and variability and to identify the origin of variations in steady states. This research was conducted from a dynamical perspective, that is, by analyzing the temporal course of discrepancies between the perceptual configuration and its memory (accuracy) and the temporal course of discrepancies between 2 successive memories (variability). In Experiment 1 the stimulus (12 black dots randomly disposed) was presented repeatedly to assess the general evolution of accuracy and variability. In Experiments 2 and 3 memory accuracy and memory variability were separated to identify their relationship. In Experiments 4 and 5 memory variability was studied to determinate the origin of steady state variations. Results show that memory accuracy and memory variability evolved independently and that memory variability reached a threshold that was subject-dependent. The dynamic properties of image construction and stability are discussed.

Visuospatial memory and mental images are tightly linked. *Memory* can be defined as the preservation in time of internal representations (mental images) that are elicited in the absence of the corresponding object and are based on processes with characteristics closely resembling those of perception (Finke & Kosslyn, 1980; Finke & Kurtzman, 1981a, 1981b; Kosslyn, 1973; Shepard, 1975; Shepard & Chipman, 1970). In research on the interrelationships between mental images and cognitive processes, the focus has been mainly on the degree of accuracy between the mental image and the stimulus. Numerous analogies have thus been drawn between visuomental images and visual perception (for a review, see Finke & Shepard, 1986). These analogies concern the preservation of structural properties (e.g., the metric characteristics of the stimulus; Kosslyn, 1975; Kosslyn, Ball, & Reiser, 1978; Pinker, 1980) as well as functional properties (e.g., rotation; Cooper, 1976; Shepard, 1978; Shepard & Metzler, 1971) or interactive properties (e.g., the influence that imagery has on performance during perception tasks; Finke, 1979a, 1979b). However, in different tasks such as configuration reproduction (Gale, 1982; Lloyd, 1989), distance estimation (Holyoak & Mah, 1982; Howard & Kerst, 1981), and orientation estimation (Hintzman, O'Dell, & Arndt, 1981; Moar & Bower, 1983), the results have shown that the metric properties of the stimulus are not retained in memory. The attention has been focused on the constraints (often short term) linked to perceptual organization principles (Tversky, 1981; Tversky & Schiano, 1988) and the constraints (more long term) linked to image elaboration, retention, and recall (Kosslyn, Backer Cave, Provost, & Von Gierke, 1988; Kosslyn, Pinker, Smith, & Shwartz, 1979; McNamara, 1986; McNamara, Hardy, & Hirtle, 1989), which are such that the image cannot be absolutely identical to the percept. Implicitly, it has been considered that when the learning process is over (i.e., when the level of accuracy no longer evolves), the image has been formed (i.e., it is stable and consequently displays a high level of consistency across trials). In other words, when the learning process is over, recall would lead to the same memory.

However, variability is inherent in all biological systems. Therefore, researchers know that when a person is asked to recall the same memory several times in succession, what is recalled is never identical. Using a serial reproduction protocol, Bartlett (1932) showed short stories or figures that the participants had to memorize. The object was then removed and he or she had to reproduce it from memory. The resulting production was used as a new inductor for a second reproduction, and so on, for several successive reproductions. The results showed that at the beginning, there were major changes from one reproduction to the next. Afterward, both the figure and story reproductions became schematized and stabilized. The changes from one reproduction to the next were thus less great, but they continued to be present. This image variability in the steady state has been classically considered as the expression of variations randomly distributed around a stable reference. It has been measured, for example, by the variable error (Schutz & Roy, 1973) or more generally by the standard deviation. However, these results suggest that researchers distinguish between image accuracy (independent of accuracy level) and image

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variability when the learning process has ended (i.e., when in the steady state). Reproductions can be always right or always wrong, but they are nevertheless always different.

Visuospatial memory permits this type of analysis because it is possible to distinguish between the accuracy of an image and the variability of that image. Indeed, when a participant must reproduce the same configuration several times, the time course of the discrepancy between the produced configurations and the required configuration provides an indicator of changes in performance that can then be used to characterize the learning of a target configuration. This indicator is expressed by a distance between a percept and its recalled image. When the distance no longer evolves, the performance indicator expresses the achieved level of accuracy (i.e., the discrepancy between the metric properties of the target configuration and the metric properties of the recalled images of that configuration). Now, if one measures the distance between the reproduced configurations themselves (i.e., independent of the target), one would obtain a variability indicator whose time course expresses the process by which information is organized in memory. When this indicator no longer evolves (i.e., when the variability between productions stabilizes), the observed values express the achieved level of image consistency. This stable variation expresses the continuous change of angles and distance ratios between any given image of the target and the next image of the same target. Note that this notion of a steady state makes sense only when one considers a limited temporal span. A steady state is an equilibrium state that depends on the temporal scale under consideration. Thus, in this case, a situation without learning or forgetting can occur when one considers a temporal window within the span of an experiment.

It was in this perspective, close to Bartlett's (1932), that we tried to identify the level of image consistency (i.e., in steady states) in relation to the accuracy level (Giraudo & Pailhous, 1994). The task consisted of learning a spatial configuration and then reproducing it from memory as precisely as possible immediately after the end of the learning phase. The task was repeated several times. Image accuracy was measured by computing the distance between each produced configuration and the target configuration, and image consistency was measured by computing the distance between the produced configurations themselves. The results showed first that, as expected, the participants were in a steady state. The distance between the required configuration and the participants' reproductions did not vary statistically. As a result, we could consider that the memory was perfectly stabilized (at least during the span of the experiment). However, we observed, on average, that the distance between the produced configurations was as large as the distance between the configurations and the percept. In other words, the participants produced response patterns as scattered as they were inaccurate. This dispersion was too large to be considered the result of minor changes (Portugali, 1996) or differences in detail (Polster, Nadel, & Schacter, 1991). Two conclusions can be drawn from these results. (a) Studying visuospatial memory with a single trial often leads to considering as inaccuracy what in reality is the outcome of variability. (b) Image variability and the accuracy of that image must be considered as two distinct phenomena whose respective properties and possible common points and differences must be identified. However, studying the respective properties of image variability and image accuracy required that the role and status of variability be reconsidered.

Numerous researchers have examined perceptual and mnesic processes from a dynamical perspective (Bartlett, 1932; Burnham, 1903; DeCamp, 1915; Hebb, 1949; Köhler, 1947; Lashley, 1950; Loeb, 1901/1973) that led to considering variability as the normal consequence of these processes. In contrast, recent researchers in cognitive psychology have focused more on performance patterns as detectors of system functioning (Tulving & Bower, 1974) than on variability, which is generally considered to exhibit random variations that make generalization of the studied phenomena difficult. By focusing on performance patterns, research on visuospatial memory has naturally evolved toward theoretical models that consider behavioral output as the direct expression of mental processes and has based the study of spatial imagery on the assumption that mental images do not present intrinsic fluctuations.

Kosslyn et al. (1979) assumed that visual images were equivalent to configurations produced on a CRT by a computer program operating on stored data. They then assumed that there were two data structures and a set of procedures operating on the data. If the image appeared variable (at the behavioral output level), this could express information instability only in long-term memory. Indeed, because there was no reason to believe that the procedures (e.g., the routines of a computer program) could be variable, and given that the structures, by definition, are invariable (as in all hardware), only the instability of the information in long-term memory could be the cause of the variability observed at the behavioral level. They found that the performance pattern thus appeared to be the best detector of the system's state and that the operations that could be applied to the images were the best detector of the system's properties.

As a consequence, variability has generally been likened to Gaussian noise without particular meaning (as the systematic use of standard deviation shows). Indeed, insofar as the standard deviation is not an index that describes a temporal continuum (i.e., an index of the system's evolution across trials), it does not provide information about the relations between trials, but only about the degree of variability for a given parameter of the system. The greater the standard deviation of the measured variable, the higher the noise level in the system (Newell & Corcos, 1993). Although such a procedure fulfills a statistical need, it considers intraindividual variations only in terms of error (i.e., as a random and thus useless noise that must be eliminated or at least minimized). The introduction a few years ago of time series analysis (i.e., dynamical analysis) in the behavioral sciences offers new perspectives by giving a significance to these variations.

A time series analysis is a collection of observations or responses considered sequentially in time (Chatfield, 1975). Whether continuous, when observations are made continuously in time, or discrete, when observations are made at specific, equally spaced moments, a time series has the following properties: (a) Observations are ordered in time. (b) The behavior of the series, at a particular moment, is affected by its behavior at the previous moment. (c) Future observations are determined, in a certain way, by both present and past observations. Consequently, studying a set of observations in the form of a time series amounts to admitting that trials are not a simple random factor and that there is a structure in the trial-to-trial relationship. In this context, only the analysis of instantaneous response variations allows the researcher to identify this structure. Because mean variation provides no information about the temporal order of the events, it can show the importance of noise in the system, but it indicates nothing about the nature of this noise (Spray & Newell, 1986). The question raised can be expressed in the following way: Does learning allow for the development of a stable mental image without intrinsic fluctuations, in which case the noise in the system is only an exogeneous random variation (i.e., time independent). Or is it the mental image that is time dependent, in which case the noise in the system is in part the expression of an intrinsic instability of the mnesic system?

The question of image properties—an important one—thus masks a preliminary question: What condition must the mnesic system fulfill for an image to be stored in memory? The ability to reproduce a stable memory thus seems crucial. It is in this perspective that we analyzed the dynamics of the accuracy of an image on the one hand and the dynamics of its variability on the other. The goal was to identify the respective properties of accuracy and variability and their possible commonalities and differences. We thus considered the perceptual configuration as an input variable and the time courses of image accuracy and image variability as output variables. We manipulated the input variable to observe the differential effects on the behavioral output on image accuracy and image variability.

Accuracy and Variability of Mental Image

Experiment 1: Correlation of Processes

The variability of a memory or of a movement is often considered to be an index of performance. One typically considers that variability decreases as a function of experience (Golledge, 1987) or practice and skills (Schmidt, 1988). In this context, when a participant learns a perceptual configuration, if he or she is systematically given feedback about the result in the form of the repeated presentation of the required pattern trial after trial, the produced pattern will be closer to the required pattern. In parallel, the patterns produced in succession will be closer and closer to each other. When the learning process is over, that is, when, after several trials the discrepancy between the produced pattern and the required pattern is constant, "the image" of the configuration stabilizes. The goal of Experiment 1 was to determine how the discrepancy between the successively produced patterns would evolve, that is, what would happen to the variability of an image when the learned configuration had become stable.

Method

Participants. Eight adults (4 women and 4 men) participated in the experiment. Their mean age was 32 years (range = 22–46 years).

Material. The material consisted of a blank sheet of plastic-coated paper with a circular shape (28 cm in diameter) containing a pattern of dots. The pattern was composed of 12 black dots (1.2 cm in diameter). The paper was glued to a blue piece of cardboard (32 × 32 cm; see Figure 1).

Procedure. Participants worked individually. The pattern was presented vertically for 5 s, and the participants were told to memorize this pattern. After the 5 s had elapsed, the pattern was removed and replaced by a blank response sheet (same size and same material). The participants were then given 12 small black dots (also 1.2 cm in diameter), and their task was to reproduce the pattern as accurately as possible by placing the dots on the response sheet. They were given as much time as they needed to perform the task and were allowed to correct their answer as many times as they wished. Each participant performed the task 40 times. The 40 trials were divided in two sets of 20. Participants studied the pattern 20 times, each time for 5 s and between each target presentation performed the task. From Trial 21 on, they did not see the pattern again.

Data processing. Two distinct measures were computed. By comparing the configurations, we could focus on both the discrepancy between each response of each participant and the target configuration (the form to be learned) and the discrepancy between the series of configurations produced. The latter amounted to comparing each configuration with the immediately previous one (see Figure 2).

The first measure is called the "accuracy measure." By comparing each configuration produced with the target configuration and

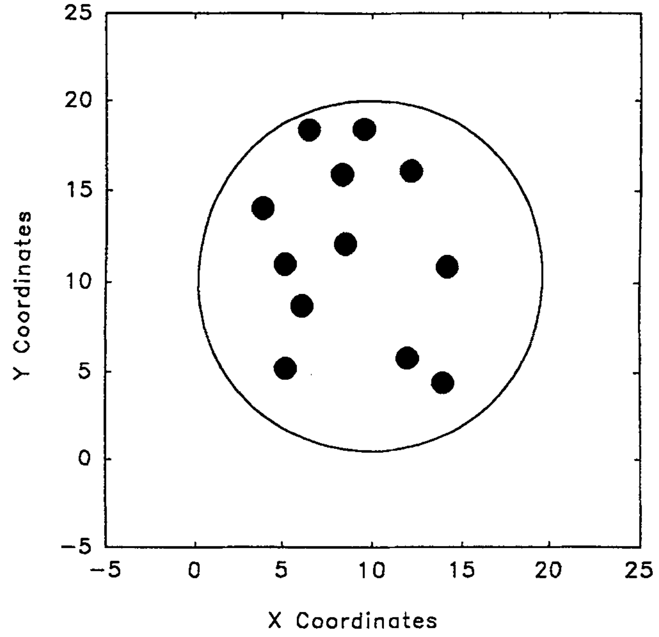

Figure 1. Spatial configuration presented to participants with the locations of 12 points. After a preliminary experiment testing several configurations of randomly distributed points, we retained this configuration because it was the configuration farthest from being a "good form" according to gestalt.

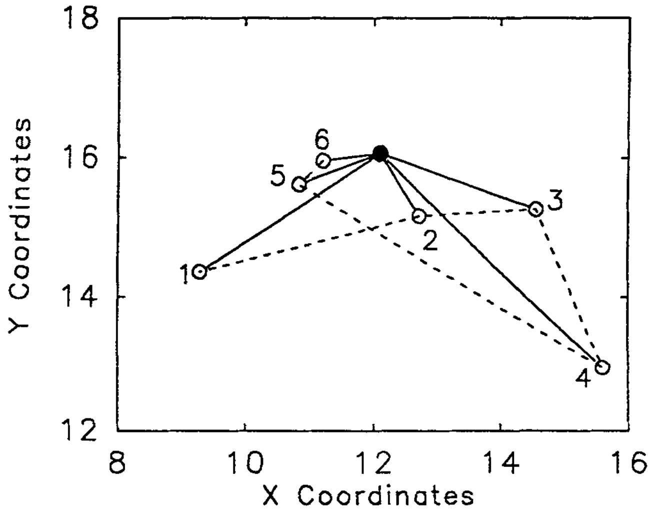

Figure 2. Illustration of the two performed measures from one dot and with 6 trials. The filled circle represents the real location of a dot, and open circles represent the successive locations estimated. Solid lines represent the distance dividing the participant's estimate from real location, and dashed lines represent the distance dividing two successive estimates. The distance between two responses thus evolved from the difference to the sum of each distance to the target configuration.

measuring the discrepancy between the two, we obtained a distance whose changes across time was an indicator of the accuracy level evolution. The second measure, which we call the "variation measure," compared each configuration with the immediately previous one (i.e., independently of the target). We thus obtained a new distance whose changes across time allowed us to study the evolution of the configuration variability level (see Figure 3).

To compare the configurations and not the absolute discrepancy between the locations, we analyzed the data with a bidimensional regression program (see Figure 4) that was developed by Tobler (1976, 1977, 1978a, 1978b). This program uses Euclidean transformations (e.g., translation, rotation, and scale change) to minimize the discrepancy between the configurations considered two at a time. The program is conceptually similar to the program used by Kosslyn, Pick, and Fariello (1974) and the calculations performed by Pani, Zhou, and Friend (1997).

The method is based on the following principle: Let Z and W be two spatial configurations, where Z is the reference configuration containing *n* points with coordinates (Xi, Yi; here, the target configuration), and W is the image configuration with *n* homologous points with coordinates (Ui, Vi; here, the participant's configuration).

Each point is thus defined by two numbers on each configuration. The discrepancy between these two configurations can be schematically represented by a vector (**Xi, Yi**), (**Ui, Vi**). The problem is to find the relationship between the reference configuration (Z) and the image configuration (W), that is, the function $\hat{W}$ of Z, which is the best fit for the image configuration (W). The two configurations are fit to each other as variables are fit in unidimensional regression. The best fit is found by minimizing the differences between the image configuration W and the fitted image configuration $\hat{W}$. This method yields three distinct homologous configurations: the original configuration, Z (the reference); the initial configuration, W (the image); and the fitted configuration, $\hat{W}$ (the fitted image), where selected points can be compared. Finding the best fit involves relating W to Z by a function $\hat{W} = f(Z)$, such that the projection of Z onto $\hat{W}$ is as close as possible to the projection of Z onto W.

The regression program provided an indicator of the mean discrepancy between the two configurations being compared (root-mean-square error [RMSE]), as well as an indicator of the discrepancy at each point. The RMSE indicator, which expresses a distance, represents the overall discrepancy between the two configurations, defined as the spatial relationships (angles and distance ratio) between the different elements of which they are composed. The discrepancy indicator for each point, also a distance, represents the various local discrepancies between the two configurations. The value of RMSE (i.e., the mean discrepancy between two configurations) depends directly on the local discrepancy value (i.e., the discrepancy between each pair of points), but a reduction in the overall discrepancy does not lead to a reduction in each local discrepancy as it can be seen on Figure 5.

Results

Analysis of the memorization process: Accuracy measure. To distinguish memory errors from perceptual-motor errors, we had 2 participants perform a simple copy task with 6 trials per participant (12 trials total). Participants looked at the target configuration and were asked to reproduce it as accurately as possible. The observed mean value of the RMSE indicator, which corresponds to the mean distance for all points, was 0.41 cm (measured on the response sheet; *SD* = 0.12 cm). This value thus provided the maximal accuracy threshold.

The accuracy measure was used to study the evolution of the distance between the target configuration and each response configuration across trials (i.e., over time). When the computed value was high, it meant that the discrepancy between the two configurations was great. In contrast, the lower the computed value, the smaller the discrepancy between the configurations. Therefore, the RMSE curve illustrates the discrepancy increase or decrease between two configurations. The RMSE indicator was first computed for each participant and then averaged to give a mean value. The significance level for those means was less than or equal to .01.

The results (see Figure 6A) show that for the first trial the mean value of the RMSE indicator was 2.01 cm (measured on the response sheet; *SD* = 0.57 cm). Given the distance to the pattern of dots 1 cm represents approximately 1°. The learning phase was considered to be terminated when performance stabilized (i.e., when there was no further performance improvement over several trials). This involved determining the learning phases as well as the steady state phases.

Regarding the identification of steady states and learning phases, we used the procedure developed by Pailhous and Bonnard (1992) to identify steady states. The difference between each trial (*n*) and the subsequent trial ($n + 1$) is computed. When the mean of these differences was close to 0 (0 ± 0.009), this attests to the presence of a steady state. In contrast, if the mean was outside this interval, it meant that there was a positive or negative tendency. In our case it was the difference between two consecutive RMSE values (e.g., the distance between the target configuration and the configu-

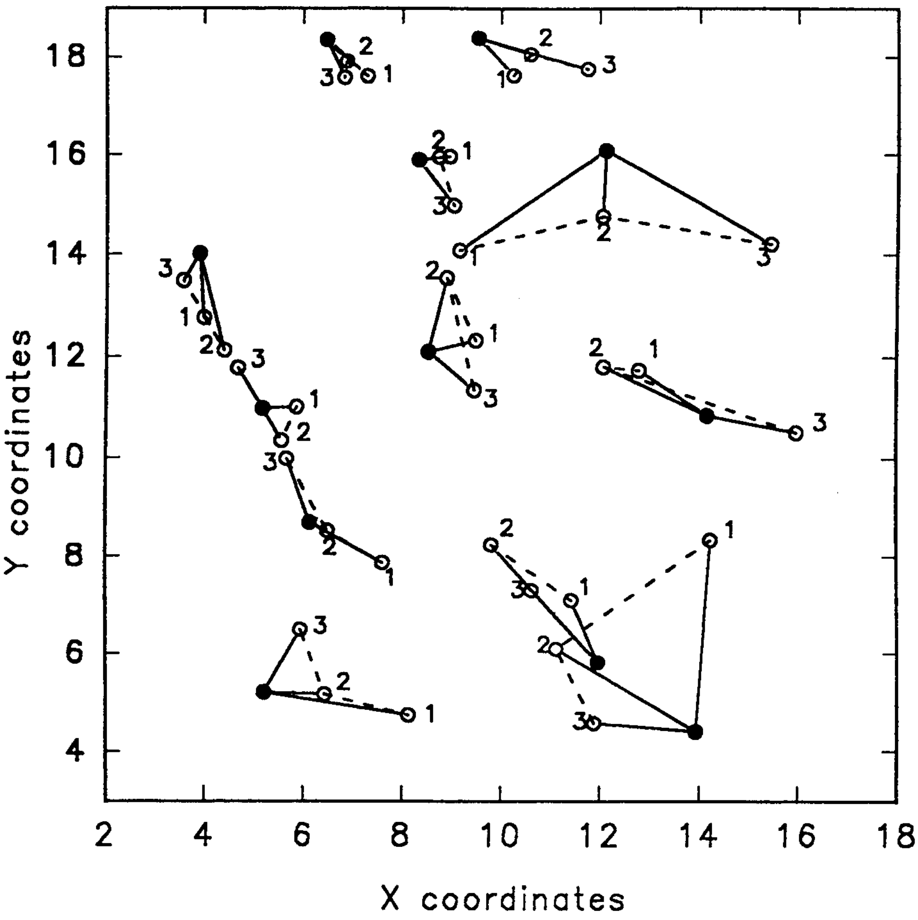

Figure 3. Illustration of the two measures computed for the 12 dots (i.e., the configuration) on 3 successive trials. The filled circles represent the real locations of the dots (i.e., the required configuration), and the empty circles represent the successive locations of the dots (i.e., the estimated configurations). For each dot, the solid lines represent the distance between the dot and the estimated dot locations on each trial. The accuracy measure for each trial is equal to the mean of these 12 distances. For each dot, the dashed lines represent the distance between two successive estimated dot locations. The response-variation measure for each pair of trials is equal to the mean of these 12 distances.

ration produced on Trial 1 and the distance between the target configuration and the configuration produced on Trial 2). In the current case, a positive tendency meant that the discrepancy in distance between the target configuration and the response configuration decreased from one trial to the next, as participants got closer and closer to the form to be learned. In contrast, a negative tendency meant that the discrepancy in distance increased from one trial to the next, as participants moved farther and farther away from the form to be learned.

The results (see Figure 6A) show that at the final state the mean value of RMSE was 0.94 cm (*SD* = 0.20 cm) and that the improvement in accuracy was about 50%. We then look at the dynamics of this process.

The mean for the first 7 intervals was 0.143 cm per step (the mean tendency value). Participants were in a learning phase and the response configurations were closer and closer to the form to be learned. Starting from the 8th interval, the results show that participants were in a steady state and that the response configurations did not get closer to the target (see Figure 6A). The maximal level of accuracy was quickly achieved with a gain of 1 cm (this level was obtained by multiplying the mean tendency by the number of intervals; here, 0.143 × 7), so the 13 trials on which the participants still saw the target before each response were not useful in improving accuracy.

The mean of the 32 intervals corresponding to the steady state was 0.0047 cm per step (*SD* = 0.07 cm). However, from Trial 21 on, participants no longer saw the target configuration before each response. This change did not disturb responses and showed that the configuration was perfectly stable in memory. Finally, the small difference between the gain computed from the tendency (0.96 cm) and the observed gain (1.15 cm) obtained from the difference between RMSEs on the first (2.01 cm) and last (0.86 cm) trials was the consequence of a marginal gain produced

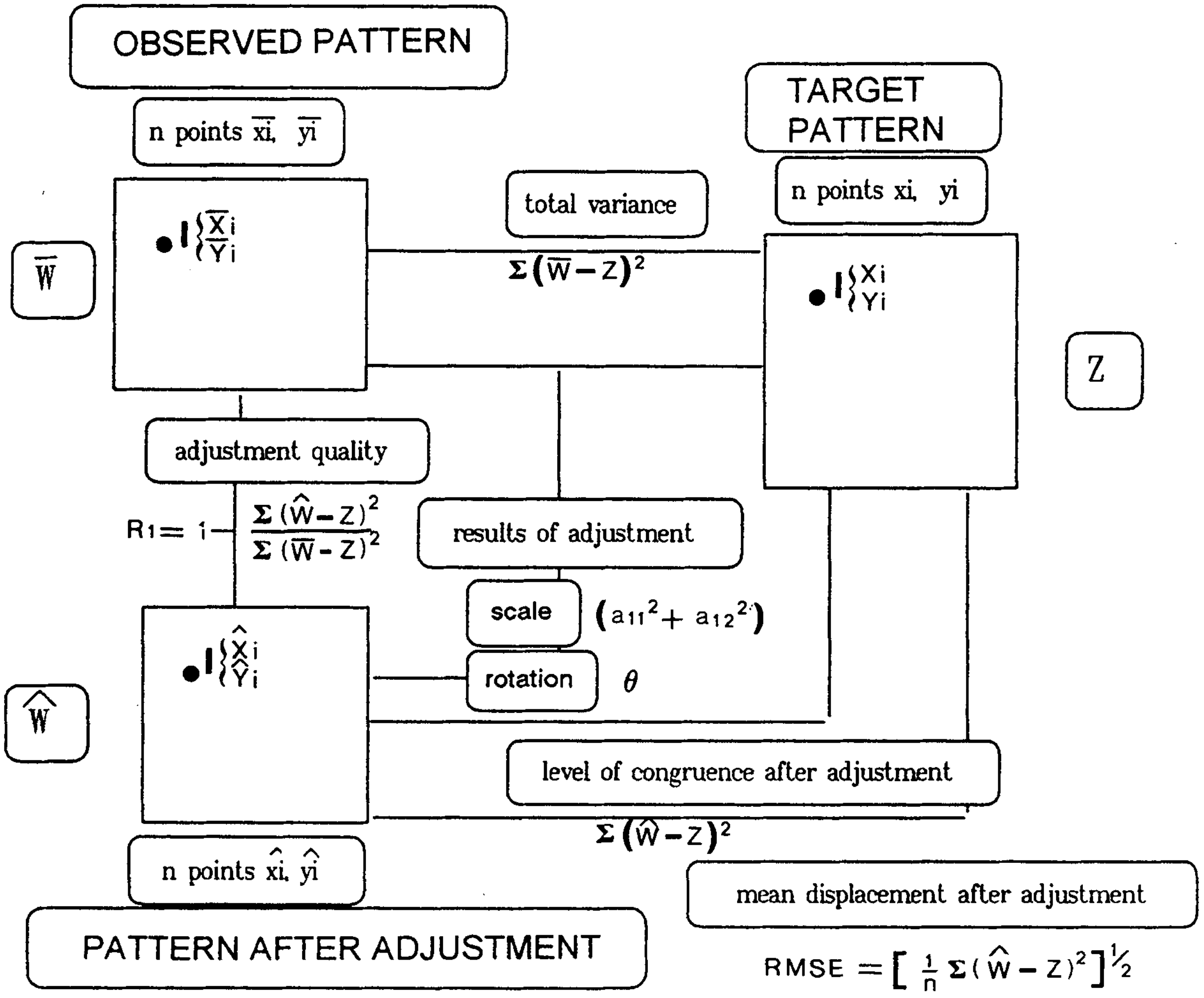

Figure 4. Measurement of congruence level in the bidimensional regression. The total variance corresponded to the discrepancy observed for the comparison between the target configuration (Z) and participants' response, that is, observed configuration (W). Adjustment consisted to perform euclidian transformations (rotation, translation, scale) on the observed configuration (W) to reduce total variance. Adjustment modified x and y coordinates of the observed configuration (W), thus producing a new configuration that we call ($\hat{W}$). The comparison brought now on the discrepancy between $\hat{W}$ and Z and numerical indicators expressed the congruence level between the two configurations ($\hat{W}$ and Z), the scale level necessary for a closeness, the rotation level, and the root-mean-square error (RMSE) distance, which distinguished the participants' response from the target configuration after adjustment.

during the steady state (0.0047 cm per step for 32 intervals; i.e., 0.15 cm).

Analysis of the memorization process: The variation measure. The variation measure was used to study the evolution of the distance between two configurations consecutively produced by the participants, independent of the target. In this case, we were interested in another aspect of the dynamic of the memorization process. Indeed, we were no longer studying the time course of accuracy (i.e., the evolution of the produced configurations toward the required configuration) but the change between one configuration and the next. In other words, we studied the organization in time of the image itself, which can be defined as a structuring process. The procedure consisted of considering each previous response configuration as the target and each new response configuration as the response. Comparing the response configurations two by two resulted in 39 new measures, for which the RMSE value was the variation measure.

The results (see Figure 6B) show that for the first variation measure, the mean RMSE was 1.71 cm (*SD* = 0.42 cm), whereas at the final state, the mean RMSE was 0.57 cm (*SD* = 0.21 cm). The decrease in the distance between responses was about 70%. As with the accuracy measure, we then looked at the dynamics of this aspect of the memorization process.

Regarding the identification of steady states and structuring phases, in the present case a positive tendency would indicate a decrease in the distance between responses, that is, when participants produce configurations that were closer and closer to each other (without necessarily getting closer to the target configuration).

The results (see Figure 6B) show that the mean of the first 7 intervals was 0.167 cm per step (the mean tendency value). The distance between responses became smaller and smaller, with a gain in closeness equal to 1.17 cm (0.167 × 7). From the 8th interval on, the distance between responses stopped changing and the system was in a steady state. The mean for the 31 intervals in this steady state was 0.002 cm per step (*SD* = 0.08 cm).

From the variation measure to the accuracy measure. The results show quasi-perfect parallelism between the RMSE accuracy measure and the RMSE variation measure. The correlation was significant ($r = .94$), $F(1, 37) = 265.9$. Thus, the greater the decrease in the distance between responses, the smaller the distance to the target configuration; when the distance between responses stopped changing, the distance to the target had stabilized.

However, we noticed that the decrease in the distance between responses could continue (stabilization on the 9th trial) without a decrease in accuracy (stabilization on the 7th trial). Moreover, the gain in accuracy (a decrease in distance to target) represented on average only 11% of the distance between the responses.

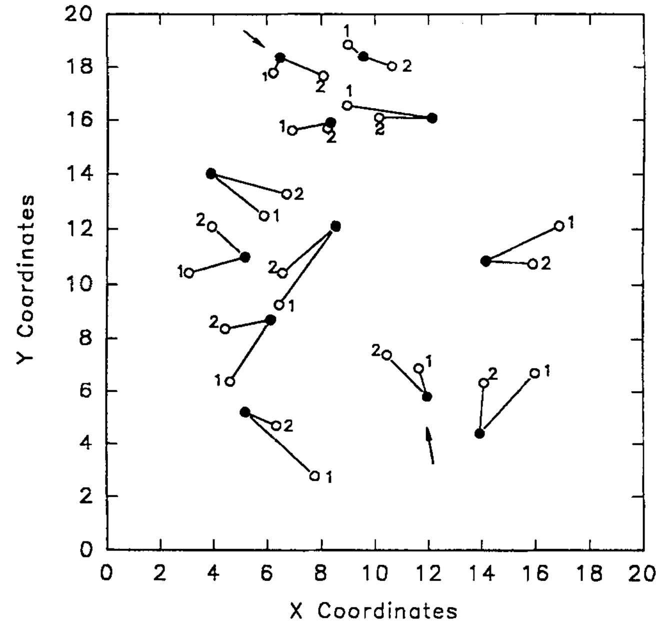

Figure 5. Result of the euclidean transformations. Filled circles represent the required locations of dots, and open circles represent the locations estimated by the participants. Solid lines represent the distance dividing the required dot locations before adjustment (identified by the number 1) and after adjustment (the number 2), showing a mean decrease of distance that can be accompanied by an increase of one or several local distances (dots identified by arrows).

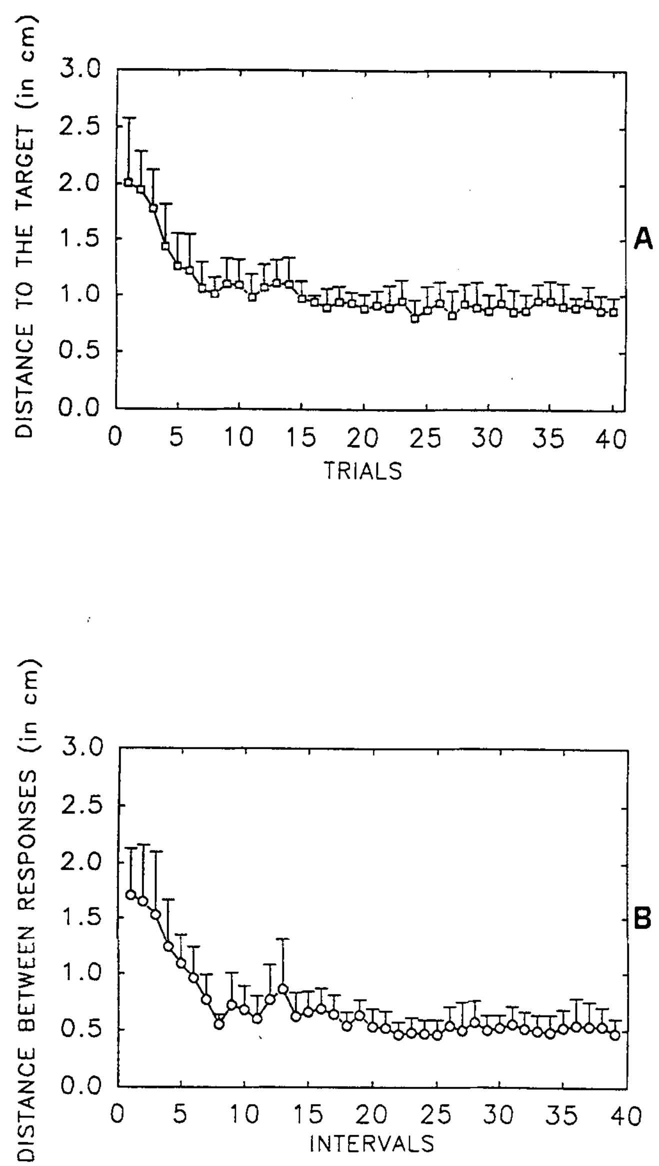

Figure 6. Evolution of the mean value of performance (A) and variations (B). Target configuration is presented between each response until Trial 20. From Trial 21 participants reproduced the target configuration without any new presentation between responses.

Discussion

The results of this first experiment show the following:

1. Increasing the number of trials to follow the creation and reinforcement of a steady state, and using the variation measure defined here—in the same way and with the same tools as for the accuracy measure—allowed us to show that the transition from a state of no knowledge to a state of knowledge was achieved by a dual process: an increase in accuracy and then a stabilization process that could be defined as a pattern migration, occurring in parallel with a structuring process (a decrease in variability then stabiliza-

tion process). Moreover, discontinuation of target presentation did not give rise to an increase in variation or a decrease in accuracy. It appeared as Adams (1971) had assumed in motor learning that the participants no longer needed to be externally "supplied" to reproduce the target configuration.

2. Variation was relatively large during the steady state (i.e., when there was neither learning nor forgetting). This result confirmed the one obtained in another experiment by Giraudo and Pailhous (1994) and suggested that the image built was blurred, as though, in reference to Kosslyn's (1978) mind's eye concept, the elaborated image was affected by a kind of "mental nearsightedness."

3. Although the variation measure seems to have a direct and univocal link to accuracy, the gain observed during the learning phase (pattern migration) with respect to variation was low (11%). These two processes, positively correlated, were confounded in our results because the increase in accuracy necessarily conveys a variability between responses. In the second experiment we tried to distinguish these two processes to evaluate the role of environmental information on the temporal course of accuracy and variations, respectively.

Experiment 2: Dissociation of Processes

The results of the previous experiment show that a mental image that reaches its maximal level of accuracy is built in parallel with a decrease in variability. In 1982, Thorndyke and Hayes-Roth, investigating new viewings, wrote about an automatic and unconscious information reorganization process in memory (i.e., trial after trial, spatial relationships between elements in an image are continuously modified to best fit the percept). Relating this to our first experiment, we can regard the systematic presentation of the target configuration between each trial as a series of new viewings allowing for the continuous reorganization of information, which leads to a decrease in variability and thus to an improvement in accuracy. This suggests that the discontinuation of new viewings will stop the reorganization process, thereby blocking any improvement. In this sense distortion, which we have defined as a stabilized state of inaccuracy (Giraudo & Pailhous, 1994), could be the consequence (because of the lack of viewings) of an impossibility for the participants to trigger or continue this ongoing reorganization process. This raises the following questions: (a) Could a stabilized state of distortion be created simply by discontinuing the presentation of the target configuration even though participants must continue to reproduce it? (b) From this stabilized state of distortion, will the resumption of viewing allow participants to continue the reorganization process, and what happens to the variability and accuracy as a consequence? (c) Will the resumption of viewing allow participants to reach levels of variability and accuracy equivalent to those observed in the previous experiment?

Method

Participants. A new group of 8 adults (4 women and 4 men) participated in the experiment. Their mean age was 31 years (range = 19–47 years).

Material. The material was identical the one used in the previous experiment.

Procedure. Each participant performed the task 40 times. They studied the pattern once for 5 s and then performed the task 20 times. From Trial 21 on, they studied the pattern each time for 5 s and between each target presentation they performed the task until the last trial. In other respects, the procedure was identical the one used in the previous experiment.

Data processing. The data processing was identical to that in the previous experiment.

Results

Analysis of the memorization process: Accuracy measure. The results (see Figure 7A) show that on the first trial, the mean RMSE (1.95 cm, $SD = 0.36$ cm) was similar to the value observed in the previous experiment, $t(14) = 0.33$, *ns.* On the final state, the mean RMSE was 0.77 cm ($SD = 0.18$ cm). Accuracy improvement was about 60%, and the distance between the target configuration and the response configurations was similar to that observed in the previous experiment, $F(1, 14) = 3.02$, *ns.*

Regarding the identification of steady states and learning phases, the results (see Figure 7A) show that for the first 3 intervals, the mean change was −0.10 cm per step. The response configuration moved away the form to be learned, with an increase in discrepancy of 0.30 cm. From the 4th to the 19th trials, the participants were in a steady state, and had a mean of 0.001 cm per step ($SD = 0.05$ cm). The mean spatial location of the response configurations at that point was 2.23 cm from the target configuration ($SD = 0.40$ cm). The distance was now significantly higher than for the first trial in the previous experiment, $t(142) = 3.67$. From Trial 21 on (i.e., from the time the participants saw the target configuration for the second time), there was a positive tendency (fitting-to-target phase) that lasted 12 intervals. The mean was 0.13 cm per step, and the response configurations came closer to the form to be learned, with a gain of 1.56 cm. From the 32nd interval to the last, that is, on the last 8 intervals, the participants were again in a steady state ($M = 0.004$ cm, $SD = 0.05$). As in the previous experiment, we found that the last series of trials on which participants saw the target configuration between each response (9 trials) had no effect on accuracy.

Analysis of the memorization process: Variation measure. The results (see Figure 7B) show that for the first variation measure, the mean RMSE (1.07 cm, $SD = 0.31$ cm) was lower than in the previous experiment, $t(14) = 4.60$. On the final state, the RMSE value was 0.55 cm ($SD = 0.17$ cm). The decrease in the distance between the responses was about 50% and was not significantly different from that observed in the previous experiment, $F(1, 14) = 0.41$, *ns.*

Regarding the identification of steady states and structuring phases, the results (see Figure 7B) show a decrease in the distance between responses on the first 6 intervals ($M = 0.08$ cm per step) that corresponded to a gain in closeness of 0.48 cm. From the 7th to the 18th intervals, the configurations did not get closer to each other and the mean of the 12 intervals was equal to 0.001 cm per step ($SD = 0.08$ cm). The distance between responses then stabilized at 0.60 cm ($SD = 0.34$ cm).

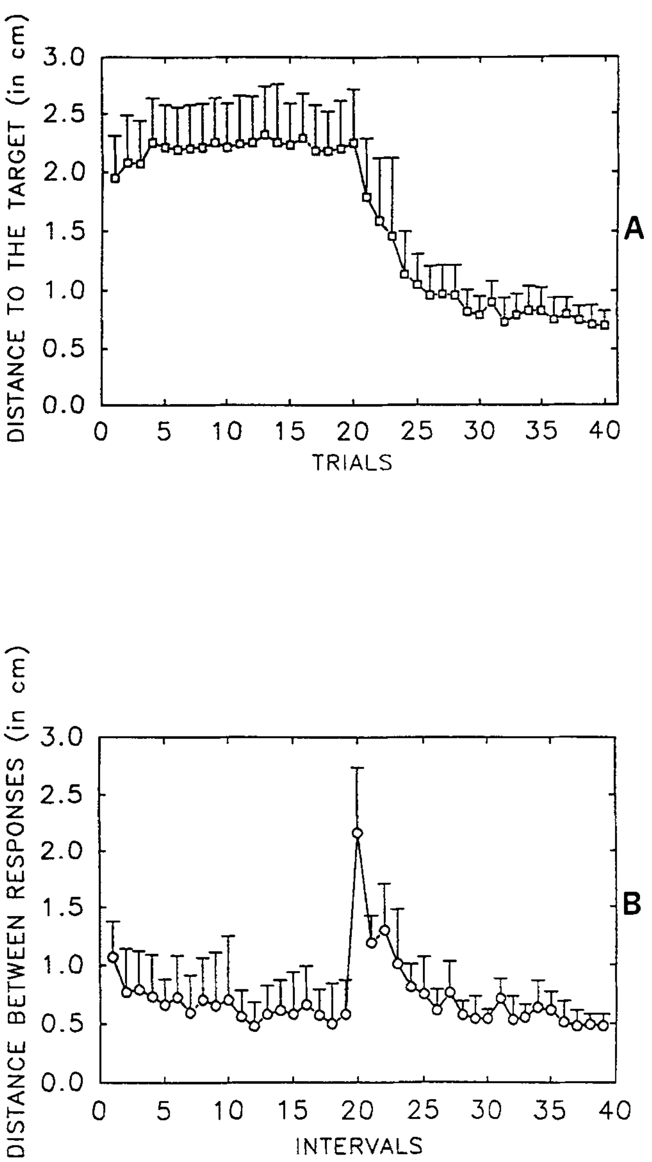

Figure 7. Evolution of the mean value of performance (A) and variations (B). Target configuration is presented one time on the first trial and the responses were performed until Trial 20 without another presentation. From Trial 21, target configuration is presented a second time then between each response until the last trial.

The variation measure between Trials 20 and 21 (the second time participants saw the target) underwent a sharp increase, which reached a value of −1.58 cm per step. This can be seen in Figure 7B at the point where the curve rises suddenly (high value for the y-coordinate), which is characteristic of a disruption in a steady state system. Apparently, the mere viewing of the target configuration a second time substantially disrupted the system.

Over the next 10 intervals, the mean was again positive and equal to 0.16 cm per step. The distance between responses decreased, and the response configurations were closer and closer to each other, with a closeness gain of 1.60 cm. This progression can be seen in Figure 7B, where the different points have smaller and smaller y-values. For the last 9 intervals, the system was back in a steady state, with a mean of 0.006 cm per step (*SD* 0.09 cm). Finally, the results show that the distance between the responses during the first steady state was not significantly different from what it was during the second steady state, $F(1, 182) = 1.14$.

From the variation measure to the accuracy measure. The results show that the correlation coefficient between the variation measure and the accuracy measure was not significant ($r = .23$), $F(1, 37) = 2.03$, *ns*. The decrease or increase in the distance between responses did not necessarily correspond to a decrease or increase in the distance to the target configuration. This lack of a correlation is easy to explain in terms of the particular phenomena observed at two points: (a) Whereas for the first few trials the distance between the responses decreased, the distance from the target configuration increased and then stabilized, before the response distance stabilized. (b) Starting from the point where the participants saw the target the second time, while the distance from the target configuration decreased normally (the observed values were comparable to the values in the previous experiment), the distance between responses increased significantly. This phenomenon was not only totally atypical during the learning phase but was also extremely short (one trial). Finally, the gain in accuracy (decrease in distance from target configuration) represented an average of 13% of the distance between responses.

Discussion

The curve for the first 20 trials showed that it was possible to create a highly stable state of distortion simply by discontinuing the viewing of the target configuration. However, for the first 5 trials, an increase in the distance to the target configuration was observed, as was a decrease in variability. This result may seem inconsistent with the idea that a decrease in variability enabled an improvement in accuracy. The accuracy drift, resulting from the lack of target presentation, can be explained by the participants' spontaneous tendency to move toward "good forms," as widely described in gestalt theories (Garner, 1962, 1970; Leeuwenberg, 1968, 1971) and hierarchical models (McNamara, 1986; Palmer, 1977), which, in dynamic-system terminology, can be called a "relaxation toward an intrinsic dynamic" (Scholz & Kelso, 1990; Schöner, 1989; Zanone & Kelso, 1992). From this point of view, the decrease in variability was made in parallel with the temporal course of accuracy. In other words, the reorganization process took place regardless of whether the response configurations moved toward or away from the target configuration.

When participants were simply given another chance to perceive the target configuration on Trial 21, a significant decrease in the distance to the target configuration was observed. This result can be explained simply by the opportunity the participants took to improve their performance. However, this improvement was accompanied by a substantial variability increase, which is characteristic of a disruption in a steady state system. It appears that when the image was stabilized in memory with a high inaccuracy level, the resumption of viewing led to a dissociation between the accuracy dynamic and the variability dynamic. It seems as though the gain in accuracy (following the viewing of the target configuration) at least temporarily required a new state of high instability, which reflects an overall modification of the relationships between the dots. As Schöner (1989) emphasized, when environmental information competes with memorized information, qualitative change in the dynamics occurs. For the subsequent trials, variability again evolved in parallel with accuracy (as in the previous experiment). These results illustrate the transition between an image of a percept and another, different image of the same percept.

On the final state, the accuracy level was equivalent to that observed in the previous experiment, as was variability level. Starting from a lower level of fit with the target, participants simply needed more trials to reach an equivalent stability level.

Regarding the distance from the target configuration, the procedure used gave us two perfectly distinct steady states. On the other hand, for variability, we could see that the two steady states were equivalent. After the disruption, variability fell back to the level it had before the disruption. Thus, the time course of variability appears to have been at least partially independent of the time course of accuracy. The third experiment was designed to verify this independence hypothesis.

Experiment 3: Independence of Processes

Results of the second experiment show that two stable and distinct levels of accuracy—and thus two distinct images—corresponded to the same level of consistency. This questions the link between the time course of variability and the time course of accuracy. Although it can be understood intuitively that a migration process cannot be triggered without a time course of variability, the reverse is less obvious. In other words, could the distance between responses evolve without an evolution of the distance to the target configuration? If the variability dynamic is not independent of the accuracy dynamic, we can expect variability not to improve if performance itself does not improve. By contrast, if these two dynamics are independent, we can assume that a decrease in variability can occur without a performance improvement. In this framework, it would not be a matter of the organization or reorganization of the image resulting from successive viewings but a question of the organization or reorganization of the dynamics specific to the memory system. The question then became, Could the accuracy dynamic be manipulated to study the variability dynamic, which conditions performance, without being confounded with it?

Method

Participants. A new group of 8 adults (4 women and 4 men) participated in the experiment. Their mean age was 32 years (range = 20–44 years).

Material. The material was identical to that used in the previous experiments.

Procedure. Each participant performed the task 40 times. They studied the pattern once for 5 s and then performed the task 20 times. On Trial 21, they studied the pattern once again for 5 s and then performed the task until the last trial (Trial 40).

Data processing. In all respects, the data processing was identical to that in the previous experiment.

Results

Analysis of the memorization process: Accuracy measure. The results (see Figure 8A) show that on the first trial mean RMSE (1.87 cm, $SD = 0.51$ cm) was not different from the mean observed in the second experiment, $t(14) = 0.47$, *ns*, or in the first experiment, $t(14) = 0.70$, *ns*. On the final state, the mean RMSE value was 1.80 cm ($SD = 0.58$ cm). Improvement in accuracy was quasi-nonexistent, and the distance to the target configuration was greater than the distance observed in the previous experiment, $F(1, 14) = 25.32$.

Regarding the identification of steady states and learning phases, the results (see Figure 8A) show that for the first 3 intervals, the mean was equal to −0.13 cm per step. As in Experiment 2, the response configuration moved away from the configuration to be learned and the increase in discrepancy was equal to 0.39 cm. From the fourth to the 19th intervals, the participants were in a steady state ($M = 0.008$ cm, $SD = 0.11$ cm). The mean distance between responses differed from the target configuration by 2.10 cm ($SD = 0.64$ cm) and was equivalent to the distance observed in the previous experiment, $F(1, 14) = 0.21$, *ns*. After Trial 21, a positive tendency equal to 0.37 cm per step was observed on only one trial, which was immediately followed by a stabilization of accuracy, for which the mean was 0.003 cm per step ($SD = 0.07$ cm).

Analysis of the memorization process: Response-variation measure. The results (see Figure 8B) show that on the first response-variation measure, the mean RMSE (1.00 cm, $SD = 0.40$ cm) was equivalent to that observed in the previous experiment, $t(14) = 0.5$, *ns*. On the final state, the mean RMSE was 0.77 cm ($SD = 0.47$ cm). The decrease in the distance between responses was about 30% and was not significantly different from that observed in the previous experiment, $F(1, 14) = 1.80$, *ns*.

In terms of the identification of steady states and structuring phases, the results (see Figure 8B) show a decrease in the distance between responses on the first 3 intervals, with a mean of 0.12 cm per step that corresponded to a gain in terms of closeness equal to 0.36 cm. Between the 4th and 18th intervals, the distance between responses was stabilized, with a mean for these 15 intervals equal to 0.001 cm per step ($SD = 0.14$ cm). The distance between responses stabilized at 0.79 cm ($SD = 0.47$ cm). At this state, the distance between responses was equivalent to the distance observed in the previous experiment, $F(1, 14) = 0.73$, *ns*.

The response-variation measure between Trials 20 and 21 (the second time participants saw the target configuration) showed a large increase that reached −1.68 cm per step. This can be seen in Figure 8B at the point where the curve

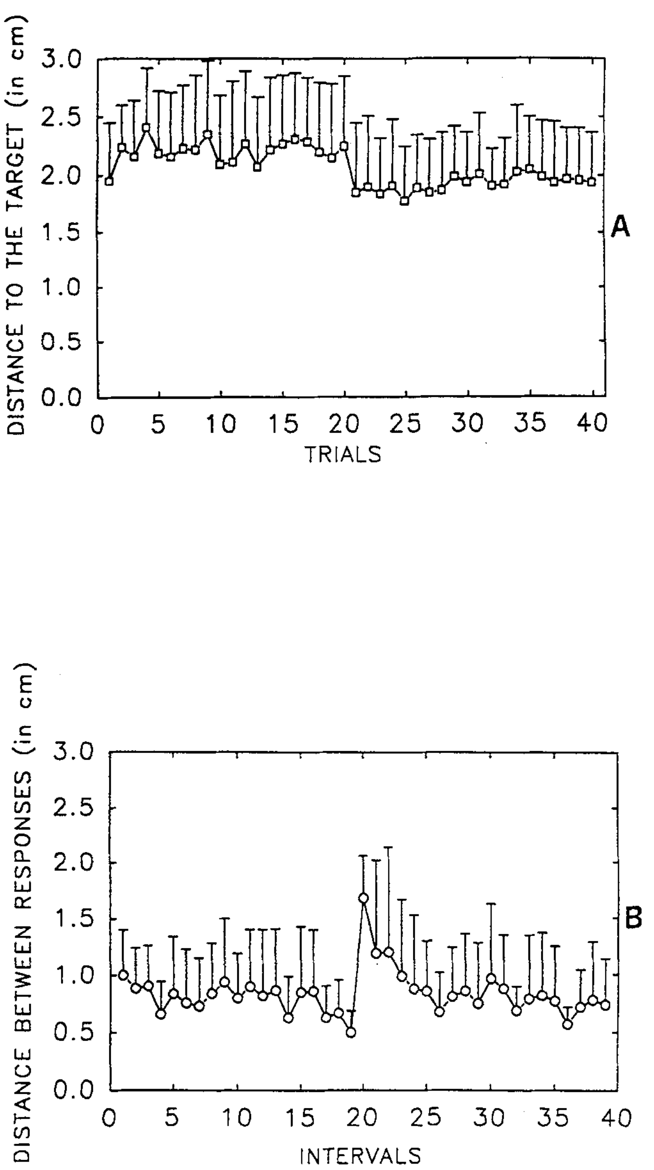

Figure 8. Evolution of the mean value of performance (A) and variations (B). Target configuration is presented only two times, a first time for the initial trial, with responses being performed until Trial 20 without any new presentation, and a second time on Trial 21, with responses being performed until the last trial without new presentation.

suddenly rises (high *y*-coordinate). The steady state system disruption linked to the mere viewing of the target a second time was of the same magnitude as in the previous experiment, $t(14) = 2.53$, *ns*. For the next 6 intervals, the mean was again positive and equal to 0.17 cm per step. The distance between responses was smaller and smaller, with a gain in closeness equal to 1.02 cm. For the last 13 intervals, the system was back in a steady state ($M = 0.004$ cm per step, $SD = 0.13$ cm). Finally, for the second steady state, the distance between responses was not significantly different from that observed for the first steady state ($F < 1$).

Discussion

The results of the third experiment confirm the hypothesized independence between the variability dynamic and the accuracy dynamic. In the steady states, after the disruption, the variability reached a level identical to that observed before the disruption, as in the former experiment. The accuracy curve showed that on the first few trials, there was an evolution toward the intrinsic dynamics that corresponded to a decrease in variability. On the last 20 trials, there was almost immediate stabilization and thus practically no improvement in accuracy, whereas the variability still decreased. Moreover, comparing the accuracy and variability curves in Experiments 2 and 3 (in which the procedure was the same until Trial 22), we found that after the disruption, the variability curves were identical in the two experiments, whereas the accuracy curves were obviously much different (see Figure 9). In other words, regardless of the initial variability and accuracy levels, the process that we have called "structuring" seemed to have reached a threshold. This threshold appeared to be a lower limit for the similarity between the successive recalls of a same image and could be defined as an image consistency level.

After manipulating the information presentation order (Experiment 2), we manipulated the number of presentations to identify the variability and accuracy dynamics as well as the relationship between them. We thus demonstrated the independence of these two dynamics and the impossibility of considering variability as an index of performance. Thus, although we learned what this relation was not, we did not learn much about what it was. In particular, we do not know the factors that could disrupt the variability dynamic, except in a temporary way, or those that could modify the level of image consistency in a long-lasting way. The two final experiments were designed to identify these factors. In Experiment 4 we examined whether the variability dynamics and the level of image consistency would depend on stimulus stability. In Experiment 5 we examined whether these two aspects of the memorization process would depend on the participants' endogeneous properties, such as age or stress.

Variability of Mental Images

Experiment 4: Instability of the Stimulus

Whatever the accuracy level, we observed the same level of image consistency. If this image consistency had been perfect (when an image is recalled twice, the second recall is strictly identical to the former) or almost perfect, as indeed computational models lead researchers implicitly to assume (Anderson, 1991; Kosslyn et al., 1979), we would have identified one aspect of the process leading to stabilized functional distortions (Ochanine, 1966; Ochanine, Quaas, & Zaltzman, 1972). However, this image consistency was not perfect (i.e., the recalled image at each moment was different from that of the previous moment). If image variability does not depend on memory accuracy, it must depend on external factors, such as the task characteristics. These characteristics

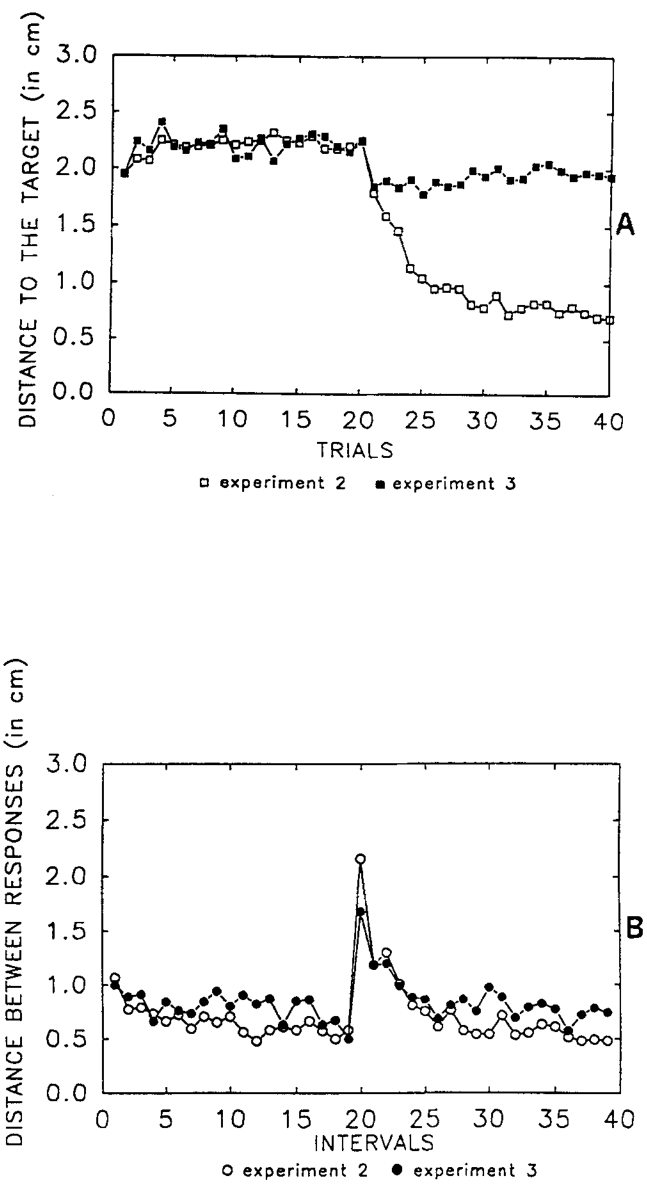

Figure 9. Compared evolution of the mean value of performance (A) and variations (B) all along trials between Experiments 2 and 3.

are candidates for explaining the participants' incapacity to recall the same image twice.

In the first three experiments, image instability was observed while the percept was perfectly stable. From this angle, we should be able to increase this image instability—a kind of mental nearsightedness—by destabilizing the percept. By presenting targets that varied randomly in time, we naturally expected that participants would produce unstable responses, with the perceptual "blur" reaching the mnesic level. Consequently, in the steady state, the threshold of image consistency should have a higher mean level than in the former experiments.

If the participant reproduced each configuration exactly, the problem would be trivial. The image consistency threshold would automatically be equal to the variations between the successive targets. However, we know that it cannot be so because the reproduction of a configuration is never totally accurate. However, some years ago, Posner and associates (Posner, Goldsmith, & Welton, 1967; Posner & Keele, 1968, 1970) showed that participants were able to classify prototypes of patterns never seen before as rapidly and as precisely as different memorized patterns that were systematic distortions of prototypes. In other words, despite extremely different targets, the participants stabilized an image in memory. Posner and associates explained this result in terms of the participants' capacity to extract an internal reference from these distorted patterns during the learning process. However, if we presented targets that themselves varied around a mean response (in the same manner that participants' responses varied around a reference in the steady state), we could expect to increase the image consistency threshold, either by making the reference (in this case, the location around which the participants' responses varied in the steady state) more difficult to stabilize or by increasing the range of variation.

Method

Participants. A new group of 8 adults (4 women and 4 men) participated in the experiment. Their mean age was 32 years (range = 22–45 years).

Material. The material was identical to that used in the previous experiments, except that instead of showing a single pattern of dots repeatedly, the participants were shown 20 slightly different patterns of dots. These 20 patterns were constructed in the following way. Considering the last 20 responses of the 8 participants who participated in the first experiment, we obtained 160 different configurations, all of which corresponded to a response produced in the steady state. Twenty configurations that satisfied the following constraints were drawn at random: (a) The mean variation between configurations had to correspond to an increase, by a factor of 1.5, in the mean variation observed in the steady state during the first experiment. Creating a continuous disruption requires giving participants the possibility of really perceiving the difference between two consecutive patterns. (b) Several different sequences had to be constructed from these 20 configurations, with the same mean and the same standard deviation. To avoid order effects, we presented the participants with the same configurations, but in different orders.

In all, four sequences were used and the mean exact variation between configurations corresponded to a distance of 0.86 cm (*SD* = 0.17 cm; see Figure 10). Participants were assigned sequences at random.

Procedure. The procedure was identical that used in the first experiment. Each participant performed the task 40 times. Participants studied each pattern for 5 s. Between each target presentation they were asked to reproduce the target as accurately as possible without being informed that the pattern was continuously changing. This was done 20 times. From Trial 21 on, the participants no longer saw any patterns but had to reproduce the configuration they had memorized until Trial 40.

Data processing. The data processing was identical to that used in the previous experiments.

Results

Analysis of the memorization process: Accuracy measure. The accuracy measure was computed between each target and each response. Consequently, only the first 20 trials were considered for the accuracy measure. Because the stimuli presentation ended at Trial 20, there was no longer a reference for valid comparison.

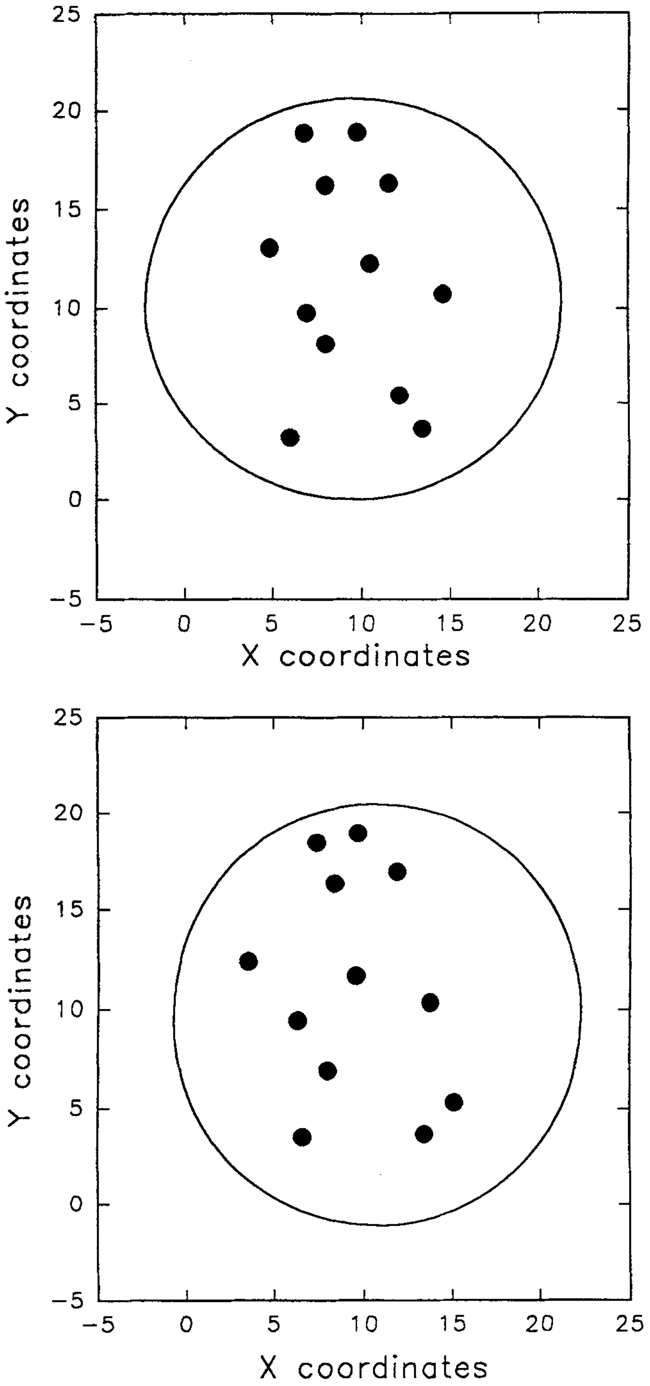

Figure 10. Example of two spatial configurations, among the 20, presented to participants with the locations of 12 dots. The configurations varied by the spatial relationships (angles and distance ratio) in such a way that each dot in a configuration had (*x*- and *y*-) coordinates different from its homologue in another configuration.

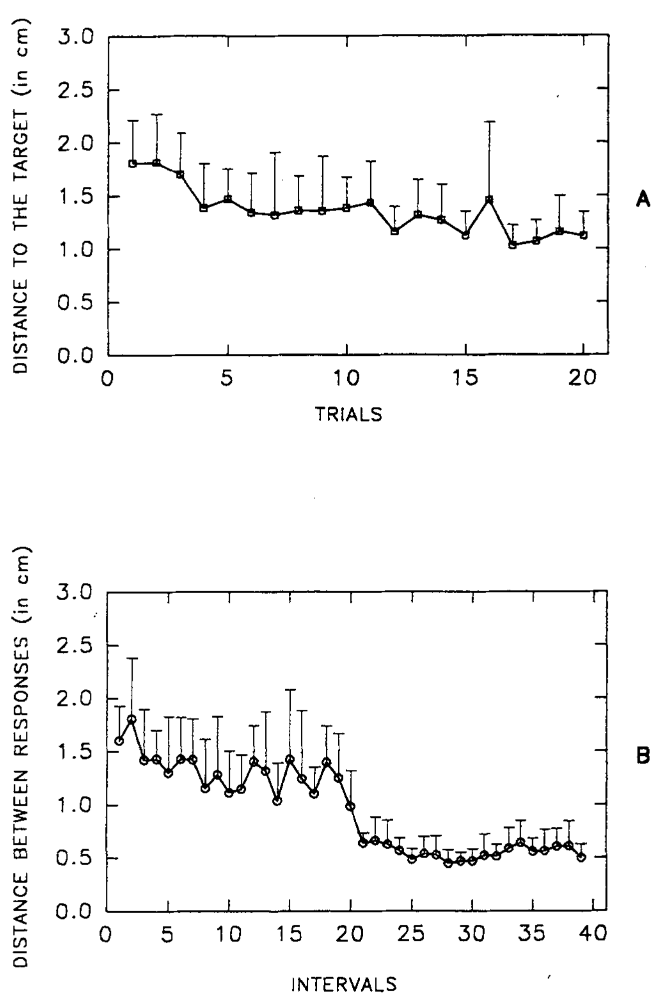

Figure 11. Evolution of the mean value of performance (A) and variations (B). Target configurations are presented between each response until Trial 20. From Trial 21 participants reproduced the "memorized configuration" without any new presentation between responses.

The results (see Figure 11A) show that on the first trial, the mean RMSE (1.81 cm, *SD* = 0.4 cm) was similar to the value observed in the first experiment, $t(14) = 0.75$, *ns*. On Trial 20, the mean RMSE was 1.12 cm (*SD* = 0.22 cm). Accuracy improvement was about 38%, although the configurations were never exactly the same and the distance between the target configuration and the response configuration was similar to that observed in Experiment 1, $t(14) = 2.53$, *ns*.

Regarding the identification of steady states and learning phases, the results (see Figure 11A) show that for the first 3 intervals, the mean change was 0.14 cm per step. The response configurations came closer to the form to be learned, with a gain of 0.42 cm that corresponded to about

60% of the total gain. From the 4th to the 11th trials, (i.e., over 7 intervals), the participants were in a steady state, with a mean of 0.007 cm per step (*SD* = 0.07 cm). The mean spatial location of the response configurations at that point was 1.38 cm from the corresponding target configuration (*SD* = 0.41 cm). From the 11th to the 20th trials (i.e., over the last 9 intervals), there was a new positive tendency (*M* = 0.034 cm per step). The gain was equal to 0.31 cm and corresponded to about 40% of the total gain.

Finally, when we considered all 20 responses, the level of accuracy was not linked to the variation of the stimuli, $r(17) = .19$, *ns*. However, when we considered the last 11 responses, the correlation became significant, $r(9) = .68$.

Analysis of the memorization process: Variation measure. The results (see Figure 11B) show that for the first variation measure, the mean RMSE (1.60 cm, *SD* = 0.32 cm) was similar to the value observed in the first experiment, $t(14) = 0.55$, *ns*. On the final state, the RMSE value was 0.55 cm (*SD* = 0.18 cm). The decrease in the distance between the responses was about 70% and was not significantly different from that observed in Experiment 1, $F(1, 14) = 0.62$, *ns*.

In terms of the identification of steady states and structuring phases, the results (see Figure 11B) show a decrease in the distance between responses on the first 4 intervals, with a mean of 0.075 cm per step, which corresponded to a gain in closeness of 0.3 cm. From the 5th to the 18th intervals, the configurations did not get closer to each other and the mean of the 14 intervals was equal to 0.004 cm per step (*SD* = 0.21 cm). The distance between responses then stabilized at 1.27 cm (*SD* = 0.47 cm). On the next 2 intervals, a new positive tendency was observed, with a mean of 0.31 cm per step, which corresponded to a gain in closeness of 0.62 cm. From the last 18 intervals, the system was back in a steady state, with a mean of 0.008 cm per step (*SD* = 0.06 cm). The results show that the distance between responses during the first steady state was significantly different from what it was during the second steady state, $F(1, 262) = 294.8$.

Finally, when we considered the first 20 measures, the variations in the responses were not linked to the variations in the stimuli, $r(17) = .30$, *ns*. However, when we considered only the steady state (from the 5th to the 18th intervals), the correlation between the variations in the responses and in the stimuli was significant, $r(13) = .67$.

Discussion

In the fourth experiment, we tried to identify the origin of image instability by considering the influence that an external factor such as task characteristics could have on the level of image consistency. By presenting targets that varied at random around a mean location, we increased spatial uncertainty on the point locations. In this context, one could expect either that the mean location around which the participant varied in the steady state became more difficult to stabilize or that the range of variation increased.

The results show that during the presentation of unstable targets, after a short structuring phase, the level of image consistency stabilized at high variation levels. By destabilizing the percept, we had thus succeeded in degrading the threshold of image consistency. Indeed, although at first the participants did not seem to be sensitive to the variations conveyed by the targets (moreover, this was reflected by the lack of a correlation), later their image instability seemed to have been directly induced by target instability (as shown by the correlation being significant). However, as soon as the disruption ended, we observed an abrupt decrease in variability. A level of image consistency equivalent to that observed in the previous experiments was instantaneously reached at that point.

In the first part of the experiment, was it a matter of an inability to stabilize a reference in memory (in which case the reference would appear as soon as the disruption ended) or an increase in variation around a stabilized reference (in which case the variation would decrease instantaneously)? Although our results did not allow us to answer this question precisely, it is likely that both possibilities were true. We have seen that image consistency, which was mediocre in the first part of experiment, improved during the first few trials. This improvement, which was close to that observed in the first experiment, reflected the onset of reference stabilization in memory despite the instability of the percepts. The spatial uncertainty in the locations of the points was so great at the beginning of the learning process that it may have totally masked the uncertainty conveyed by the targets. When the "noise" linked to the learning process had decreased enough, the signal variations could be taken into account.

We can easily conceive of the idea that the presentation of variable targets is able to disrupt a reference that is not totally stabilized. However, if it were only a matter of difficulty in stabilizing a reference, we would expect no link between the time course of the percept variations and the time course of accuracy. Indeed, given that at each trial the produced configuration largely depends on the current percept, the error should be more or less constant. In contrast, if a reference was at least partially stabilized in memory, the time course of accuracy would necessarily follow the time course of the percept variations. Whereas on the first few trials we observed an almost constant error, on the last 11 trials the higher the variation between two percepts the greater the error.

Nevertheless, we did not succeed in modifying the level of image consistency in a durable way (i.e., beyond the disruption generated by the variable targets). When this disruption was lacking, the image built by the participant immediately appeared (and was masked until that moment by the level of variability) with its usual level of consistency. Thus, after having shown that the level of consistency was both independent of accuracy (Experiments 1–3) and percept stability (Experiment 4), we thought that it might be a question of an endogeneous property (i.e., specific to the mnesic system). In Experiment 5 we attempted to verify this hypothesis.

Experiment 5: Participant Instability

Age is known to enhance intraindividual variability. In this context, age seemed to be a good dimension for approaching the problem of the level of image variability (along with other factors such as stress, e.g.). Numerous researchers (Janicke, Coper, & Schulze, 1988; Palmore, Busse, Maddox, Nowlin, & Siegler, 1985; Shok et al., 1984) have found that an increase in intraindividual variability is observed before a notable decrease in mean performance (often qualitative). However, large variability in a given behavior can cause this behavior to become inappropriate (e.g., if a participant's stride length varies too much, the adjustment that preceded the sidestepping of an obstacle can become impossible; Berg, Wade, & Greer, 1994). If steady state variations are inherent to complex systems (of which living organisms are obviously a part), their magnitude could rapidly become a decisive factor in behavioral adaptability and learning.

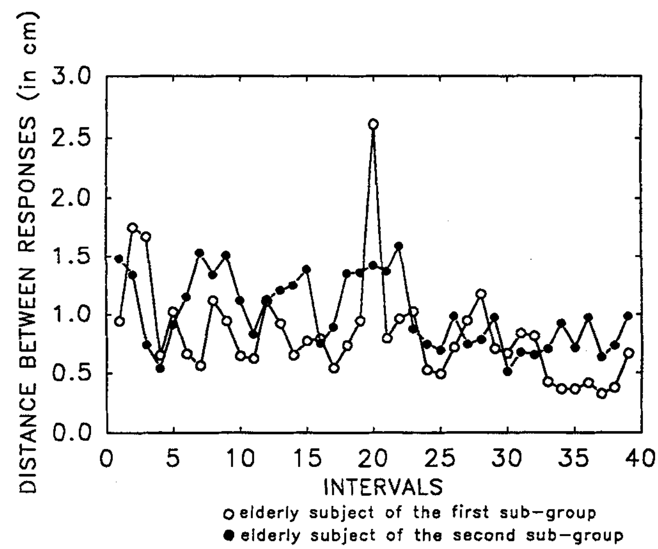

Figure 12. Evolution of the mean value of variations for 2 elderly participants showing a reaction to the presentation of target configuration on Trial 21 (the participant who belongs to the first subgroup of elderly participants) and a lack of reaction (the participant who belongs to the second subgroup of elderly participants).

Method

Participants. A group of 11 elderly adults (8 women and 3 men) participated in the experiment. Their mean age was 75 years (range = 67–84 years). They were unimpaired and were selected from a group of retired professors.

Material. The material was identical to that used in the previous experiments.

Procedure. The procedure was identical the one used in the second experiment. Each participant performed the task 40 times. Participants studied the pattern once for 5 s and then performed the task 20 times. From Trial 21 on, they studied the pattern each time for 5 s and between each target presentation they performed the task until the last trial. In all other respects, the procedure was exactly like that used in the previous experiments.

Data processing. The data were processed as in the previous experiments.

Results

The elderly participants exhibited large interindividual variability. Yet, ignoring this interindividual variability may obscure the phenomena we were attempting to study. Therefore, the elderly participants' data were considered separately before being averaged. The results (see Figure 12) show that for 4 participants, the presentation of the target configuration on Trial 21 did not produce a reaction as it did among the other elderly and young participants. Indeed, the response distance between Trials 20 and 21 was not different from the response distance on previous trials for these 4 participants. If a reaction to a disruption is characteristic of a stable steady state, however, the lack of a significant reaction reflects the instability of the steady state before the disruption.

Consequently, we divided the group of elderly participants into two subgroups. The first subgroup was composed of 7 individuals (5 women and 2 men). Their mean age was 73 years (range = 67–80 years). The second subgroup was composed of 4 participants (3 women and 1 man). Their mean age was 79 years (range = 70–84 years).

Analysis of the memorization process: Accuracy measure. The results (see Figure 13A) show that for the first trial, the mean RMSE (1.99 cm, $SD = 0.23$ cm for the first subgroup) was equivalent to the mean of the young participants in the second experiment, $t(13) = 0.33$, *ns*. In contrast, for the second subgroup (see Figure 13B), the mean RMSE (2.76 cm, $SD = 0.33$ cm) was higher than for both the young participants, $t(10) = 5.40$, and the first elderly subgroup, $t(9) = 5.90$. On the final state, the mean RMSE was 1.09 cm ($SD = 0.26$ cm) for the first subgroup and 1.64 cm ($SD = 0.55$ cm) for the second subgroup. The improvement in accuracy was 50% and 41%, respectively, but the distance between the target configuration and the response configurations in both cases was higher for the first subgroup, $F(1, 13) = 10.07$, and for the second subgroup, $F(1, 10) = 16.7$, than for the young participants. Finally, the accuracy of the first subgroup was not significantly different from that of the second subgroup, $F(1, 9) = 3.62$, *ns*.

Regarding the identification of steady states and learning phases, for the first subgroup, the results (see Figure 13a) show that the mean over the first 12 intervals was −0.04 cm per step. The response configuration moved away from the configuration to be learned, and the discrepancy increase was equal to 0.48 cm. From the 13th to the 19th intervals, the participants were in a steady state with a mean equal to 0.002 cm per step ($SD = 0.06$ cm). The response configurations were then located an average of 2.50 cm from the target configuration ($SD = 0.25$ cm), and this distance was equivalent to the distance observed for young participants, $F(1, 13) = 2.09$, *ns*. From Trial 21 on (i.e., after seeing the target a second time), a positive tendency was observed on 14 intervals, with a mean of 0.10 cm per step. The response configurations were closer and closer to the target configuration, with a gain of 1.40 cm. From the 34th to the last interval (6 intervals), participants were back in a steady state ($M = 0.007$ cm per step, $SD = 0.07$ cm).

For the second subgroup, the results (see Figure 13B) did

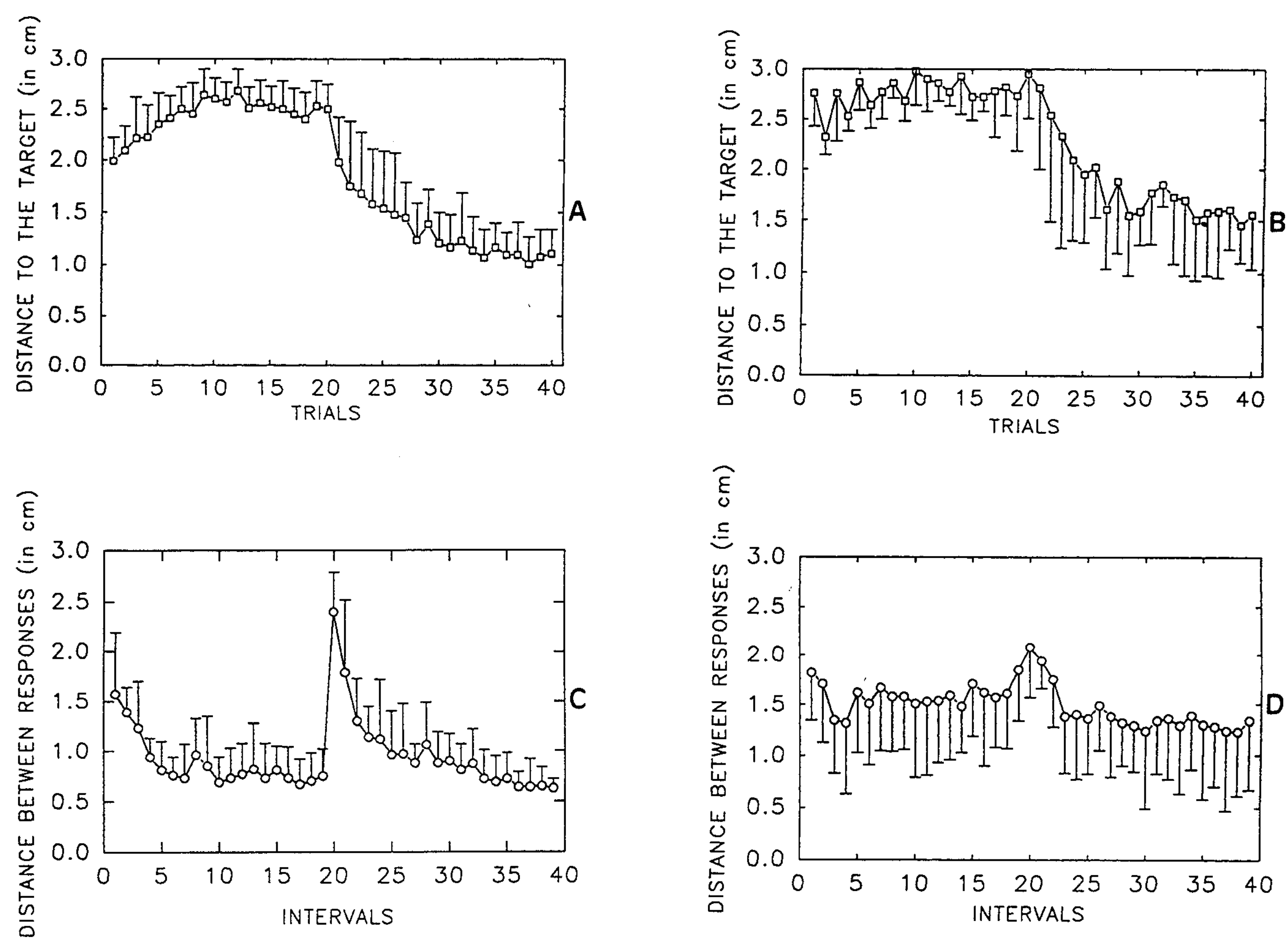

Figure 13. Evolution of the mean value of performance for the first subgroup of elderly participants (A) and for the second subgroup (B) and of variations for the first subgroup (C) and the second subgroup (D) showing the difference of behavior, particularly on variations.

not show any evolution during the first 19 intervals. Participants were immediately in a steady state ($M = 0.002$ cm per step, $SD = 0.21$ cm). The response configurations were located at an average of 2.77 cm from the target configuration ($SD = 0.34$ cm), and this distance was not significantly different from that observed both for young participants, $F(1, 10) = 6.53$, *ns*, and for the first subgroup, $F(1, 9) = 3.70$, *ns*. When participants had seen the target a second time, a positive tendency was observed on 7 intervals, with a mean of 0.19 cm per step, which corresponded to a gain of 1.33 cm. Starting from the 27th interval (i.e., over 13 intervals), the results show that participants were again in a steady state ($M = 0.004$ cm per step, $SD = 0.16$ cm).

Analysis of the memorization process: Variation measure. The results (see Figure 13C) show that on the first variation measure, the mean RMSE (1.57 cm, $SD = 0.62$ cm for the first subgroup) was equivalent to that observed for the young participants, $t(13) = 2.63$, *ns*. In contrast, for the second subgroup (see Figure 13D), the mean RMSE (1.82 cm, $SD = 0.47$ cm) was higher than for the young participants, $t(10) = 4.20$. However, between the two groups of elderly adults, the difference was not significant, $t(9) = 1.00$. On the final state, the RMSE was 0.66 cm ($SD = 0.21$ cm) for the first subgroup and 1.33 cm ($SD = 0.60$ cm) for the second subgroup, which corresponded to a distance decrease of 58% and 27%, respectively. For the first subgroup, the response distance was equivalent to that observed for the young participants, $F(1, 13) = 3.76$, *ns*, whereas for the second subgroup, the response distance was higher than for the young participants, $F(1, 10) = 9.68$. Finally, the comparison between the two groups of elderly adults did not show a significant difference, $F(1, 9) = 5.42$, *ns*.

In terms of the identification of steady states and structuring phases, for the first subgroup, the results (see Figure 13C) show a decrease in the distance between responses over the first 9 intervals ($M = 0.10$ cm per step). This corresponded to a gain in closeness of 0.90 cm. Between the 10th and 18th intervals, the responses stopped getting closer to each other and the mean was 0.007 cm per step

(*SD* = 0.06 cm). The response distance then stabilized at 0.75 cm (*SD* = 0.33 cm) and was equivalent to the distance observed for young participants, $F(1, 13) = 4.00$, *ns*. As in Experiments 2 and 3, the variation measure between Trials 20 and 21 showed a large increase in response distance that reached −1.65 cm per step, which is characteristic of a disruption in a steady state system. This disruption linked to the mere viewing of the target configuration for a second time was of the same magnitude as that of the young participants, $t(13) = 0.30$, *ns*. For the next 16 intervals, the mean was again positive and equal to 0.11 cm per step. The distance between responses decreased, with a gain in closeness of 1.66 cm. For the last 3 intervals, the system stabilized again with a mean of 0.002 cm per step (*SD* = 0.01 cm). Finally, for this second steady state, the distance between responses was not significantly different from the distance observed for the first steady state, $F(1, 96) = 2.36$, *ns*.

For the second subgroup, the results (see Figure 13D) did not show any change over the first 18 intervals. The distance between responses was immediately stable, with a mean of 0.002 cm per step (*SD* = 0.15 cm). The distance between responses stabilized at 1.59 cm (*SD* = 0.60 cm) and was significantly higher than the distance observed for both the young participants, $F(1, 10) = 14.55$, and the first elderly subgroup, $F(1, 9) = 9.79$.

As we have seen, the second viewing of the target configuration did not produce disruption, and the response distance between Trials 20 and 21 was not significantly different from the distances observed for steady state responses, $F(1, 20) = 4.11$, *ns*. Between the 20th and 22nd variation measure (3 intervals), the mean was positive and equal to 0.23 cm per step, which corresponded to a gain in closeness of 0.69 cm. For the last 16 intervals, the system stabilized again with a mean of 0.002 cm per step (*SD* = 0.08 cm). Finally, the response distance was significantly higher for the first steady state than the second, $F(1, 142) = 6.38$.

Discussion

Three important results stand out from this fifth experiment:

1. The results confirm the independence of the variability and accuracy dynamics. The variability dynamic for the first subgroup of elderly participants was in all respects similar to those of the young participants, although they never reached the same accuracy level. This result replicated the result observed in Experiments 2 and 3. Inversely, for the first part of the experiment, the accuracy levels in the steady state were equivalent for the three groups of participants, whereas for the oldest participants, the variability dynamic was different both from that of the young participants and that of the first subgroup of elderly participants. It follows not only that accuracy level cannot be predicted from variability dynamic but also that a variability dynamic cannot be predicted from accuracy level either.

2. For a configuration to stabilize, the space within which the location varies must not overlap with the variation space of neighboring points because differentiation of points becomes impossible. However, this is what happened for some of the oldest participants for whom the stimulus-to-noise ratio was too small for the points to be differentiated (see Figure 14). If at different times different points can take on the same location, or if the same location can contain different points—which is another way of saying the same thing—one can easily understand that it would be difficult if not impossible to structure an image in memory. When the structuring process cannot be triggered, no decrease in variability appeared. In the second part of the experiment, we observed a slight decrease in variability that could express a slight structuration.

3. The memorization deficit observed among elderly participants is often explained in terms of a cognitive deficit leading to the inability of these participants to spatially structure the environment (Light, 1991). However, a different but nonexclusive phenomenon may take effect. When a participant has an intrinsically unstable representation of the environment, structuring becomes impossible, not because the cognitive means of structuring does not exist but because the basis on which that structuring depends has disappeared.

General Discussion

The goal of these experiments was to study the dynamics of mental image accuracy and variability, in the same way and with the same tools, to determine the relationship between them. In particular, after showing that image variability—largely ignored in past decades—deserves to be studied (Giraudo & Pailhous, 1994), these experiments were designed to study that variability as well as its role and significance in the formation and stabilization of spatial images.

The first experiment showed that the construction of a spatial image and its stabilization in memory were achieved by a first dynamical process we have called a "structuring process" and by a second dynamical process we have called a "migration process"; these two processes seemed to evolve in parallel. In the second and third experiments, we showed that, depending on the task constraints, the image that is elaborated can appear as a simplification (under gestalt principles) of the required configuration or as a relatively accurate reproduction of it with its overall geometric properties. However, the results show that the image consistency level was independent of the accuracy level (Experiment 2) and that the time course of variability was independent of the time course of accuracy (Experiment 3). In the last two experiments we tried to deteriorate the image consistency level. The results show that the consistency level was not dependent on exogenous factors such as stimulus variability (Experiment 4) but depended instead on endogenous factors such as the participant's physiological state, assessed here through age (Experiment 5).

Dynamic of the Structuring Process

The structuring process is a process through which produced configurations become closer and closer to each other until they reach a threshold; we have called this the "consistency threshold." The triggering of this structuring

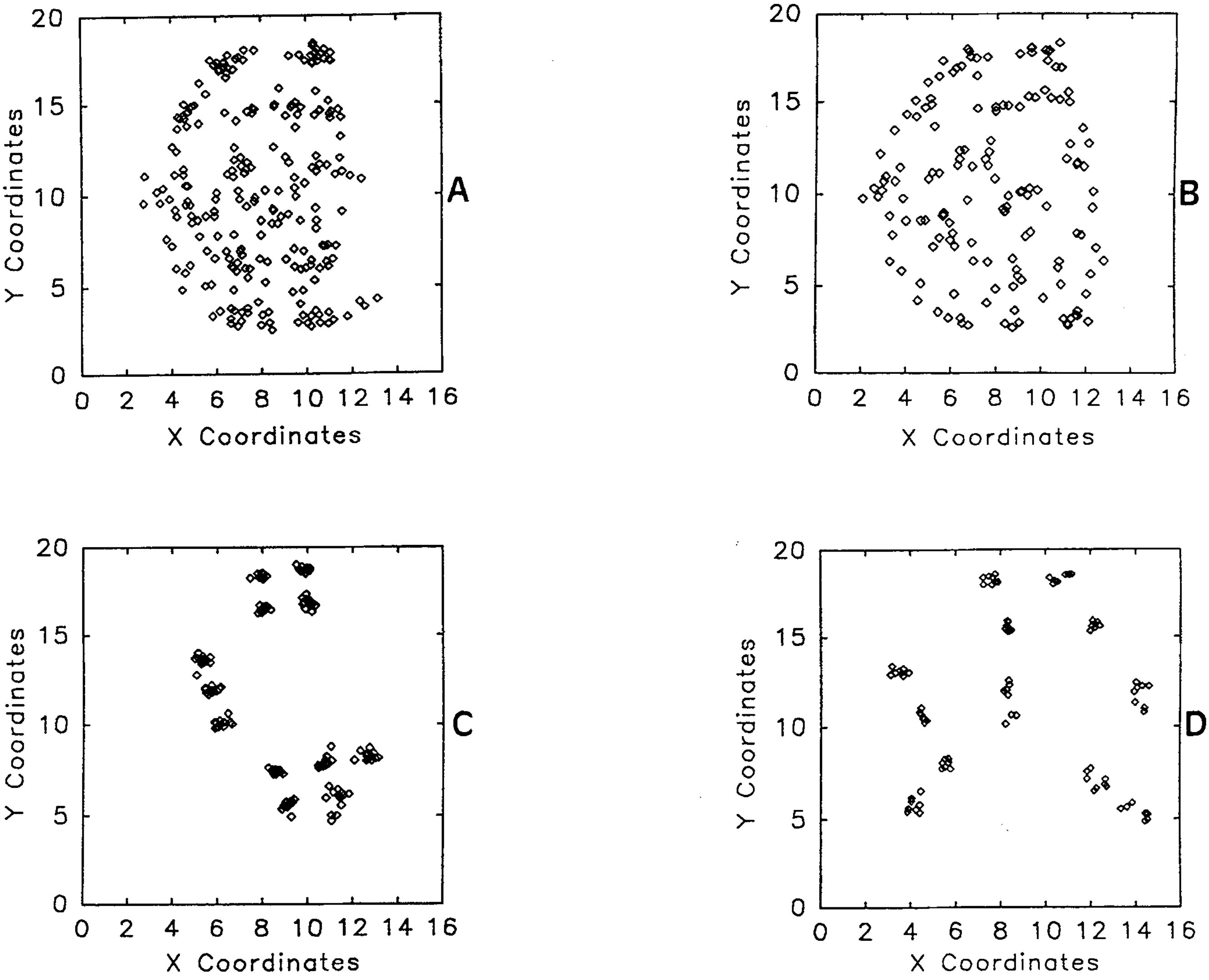

Figure 14. Spatial distribution of dots locations for the oldest participant and for a young participant. A: The reproduction phase without perception (first part of the experiment) for the oldest participant. C: The reproduction phase of a young participant in the same conditions. B: The reproduction phase with perception (second part of the experiment) for the oldest participant. D: The reproduction phase of a young participant in the same conditions.

process is a necessary but insufficient condition for the existence of a stabilized image in memory. Indeed, this process determines the emergence of an image in memory, but the triggering itself depends on an intrinsic participant-linked dimension: his or her physiological state. As shown by the results of the second subgroup of elderly participants there seems to be a maximum level of variability beyond which the emergence of a form (i.e., the identification of a cloud of points as differentiated elements) is no longer possible. As a result, an initial point-differentiation step is necessary, regardless of how close the points are (or, in this case, how far away they are) from the required locations.

Among the 4 elderly participants, no reaction was observed to the presentation of the target configuration on Trial 21. This result was not surprising. When the point locations vary so much in the participant's mind that a single location may be occupied at different times by different points, these points cannot easily be tied to each other. They will thus vary independently over time. However, the structuring process is an expression of the way in which the system constrains (and therefore reduces) the number of degrees of freedom. As Tuller, Turvey and Fitch (1982) proposed in the field of motor control, "linking elements reduces the number of degrees of freedom that must be controlled independently. This number is always smaller for a set of constrained elements than for a set of elements that are free to vary independently" (p. 265). In the same way, learning and memorizing a configuration should be conceived of as a process that constrains the degrees of freedom, that is, that creates links between the elements of the configuration, which amounts to tying them together. In other words, a cloud of points is transformed into a configuration. By reducing the number of points that can vary simultaneously, forms appeared to which a goal-directed cognition can be applied. However, this process can be implemented only if the signal emerges from the surrounding noise. When the noise masks the signal, no perceivable difference can be identified between the series of configurations produced and the new perceived configuration. Note also, anecdotally, that the oldest participants, unlike the others, did not react with surprise at the second presentation of the percept.

The construction of a mental image thus presupposes that the variability level stays below a certain threshold for the elements to be differentiated. This level then conditions the triggering of the structuring process and consequently the emergence of an image, whether accurate or inaccurate. In the field of motor control, this question has been clearly delineated: The adaptive capabilities of a behavior (i.e., its ability to be modified) are closely linked to its stability (i.e., its ability to be reproduced). As such, it is impossible to regulate the amplitude of one's stride when approaching an obstacle if one does not possess a stable basis to perform this regulation (Bonnard & Pailhous, 1993; Pailhous & Bonnard, 1992). It is thus easy to understand that if, from one stride to the next, fluctuation with a large random amplitude is observed, then one cannot modify that amplitude in a controlled way.

During the second part of the experiment, the weakness of the structuring process among the oldest participants, and even its absence for some of them, showed that the successive viewings played only a minor role in the structuring process. This interpretation was largely confirmed by the results of Experiments 2–5 (first subgroup of elderly participants). In the second part of Experiment 3, for example, the structuring process took place without viewing of the configuration to be learned. Reciprocally, in Experiment 4 the structuring process existed despite the experimentally introduced instability.

However, a decrease in variability has often been considered to be an index of performance. Although it has been established that the response dispersion is great at the beginning of the learning process and is much lower once the learning process has stabilized, this result nevertheless constitutes only one aspect of variability, the aspect that pertains to performance variability. This aspect is only a measure of the reliability with which a participant reproduces a norm, and in no case is it a measure of the genesis of the image itself. In this context, only a partial view of the learning process is available, for the indexes used in fact pertain solely to the result. By looking not at performance variability (i.e., the instability of the mnesic content) but instead at the potential instability of the image itself (i.e., the instability of the system supporting that content), we have shown that this variability is a self-generated mental activity and its decrease is the condition for the existence of mental images. In this sense, this variability is intrinsically linked to the participant and not to the task, whereas variability in performance is basically task dependent.

When the structuring process triggered, which was the case for the young participants (even if in Experiment 4 it could not be fully expressed) and some of the elderly participants, its dynamic took on the form of a relaxation curve. The configurations were thus farther apart at the beginning of the process (when the steady state was still far away) and grew closer as the steady state approached. Moreover, whatever its original level of variability and whatever the events encountered during its evolution (a single disruption or a continuous perceptual noise), the structuring process inevitably reached the same steady state. In other words, there seems to be a level of memory consistency, with a definite value (probably linked to a level of complexity, also definite). This level of consistency thus appeared as the natural state of the system. Indeed, we found that (a) the level of memory consistency is reached from different initial conditions (Experiment 1 vs. Experiments 2 and 3) and (b) the level is instantaneously reached as soon as the disruption ends (Experiment 4). The structuring process thus has its own dynamic, independent of those of the migration process.

Dynamic of the Migration Process

The structuring process was accompanied by a migration process, which defines the level of image accuracy with respect to the percept and, beyond that, provides support for studying analogies between images and perception. Although the structuring process was intrinsically linked to the participant's characteristics, the migration process appeared to fundamentally depend on the task constraints. The latter indeed appeared to be subtended either by dynamics that we call preferred or intrinsic dynamics, in reference to work on motricity (Bonnard & Pailhous, 1993; Kay, Saltzman, Kelso, & Schöner, 1987; Kelso, Holt, Rubin, & Kugler, 1981), or by essentially environmental dynamics (Schöner, 1989). When the participants had only their own responses as feedback, as in the first part of Experiments 2, 3, and 5, the configurations produced evolved, under the effect of the preferred dynamics, toward the construction of "good forms" (i.e., ones that were simpler than the configuration to be learned, which may have moved them away from the required configuration). Indeed, as emphasized by Grossberg (1978, 1980) and Schöner (1989), no external information was competing with the natural tendency of the participant to simplify. The construction of good forms as a result of the preferred dynamics is consistent with the idea defended by Stevens and Coupe (1978) and Tversky (1981) that the "distortions" observed in memory tasks are the normal consequence of information processing. The processing of a complex configuration naturally leads participants to use heuristics that allow them to simplify the configuration, especially when it is not meaningful. It is clear that in a self-referenced situation, the natural tendency of the system to simplify can only be reinforced. This natural tendency to use heuristics is manifested, as can be seen in Figure 15, by the decomposition of a complex and meaningless figure (perceptual configuration) into a subset of simple figures (e.g., squares, rectangles, triangles, etc.) ending with a formation of clusters (Hair, Anderson, Tatham, & Black,

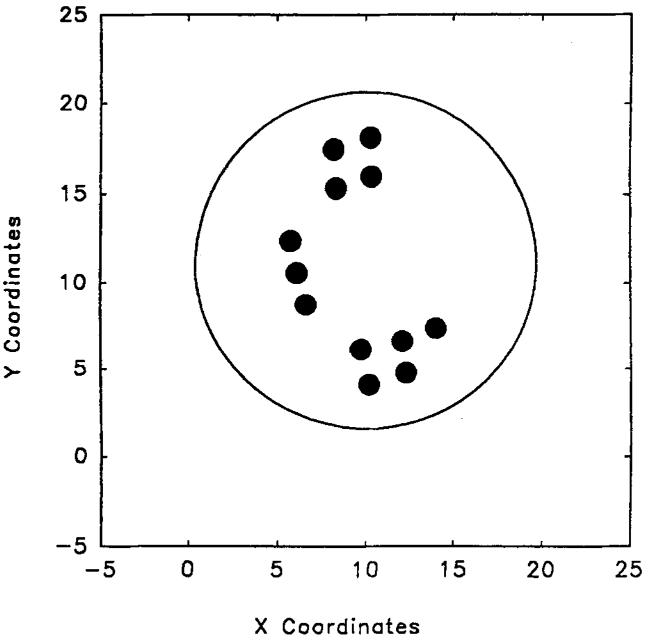

Figure 15. Response protocol (example of a young participant in the second experiment) illustrating the participants' tendency to produce simplified forms. This response was observed on Trial 5.

1992). Consequently, an image that is inaccurate or distorted relative to an external reference is in no case an incomplete, structureless, or strongly noise-filled image (Kosslyn et al., 1979). On the contrary, it is a strongly structured image with a level of consistency equivalent to that of a more accurate image. Finally, whether an image is accurate or inaccurate, its elaboration is achieved in exactly the same way; only its apparent structure changes.

When participants had as feedback not only their own responses but also the perceptual configuration, the migration process was mainly subtended by environmental dynamics. The configurations produced got closer and closer to the required configuration, as shown in the first experiment and in the second part of Experiments 2 and 5 (first subgroup of elderly participants). This reminds us of a classic viewpoint according to which experience (Evans, Marrero, & Butler, 1981; Golledge, Rivizzigno, & Spector, 1975; Siegel & Schadler, 1977) or practice and skills (Newell & Rosenbloom, 1981; Schmidt, 1988) improve performance. In our case, the accumulation of successive viewings increased the accuracy of configuration element locations and their relationships. However, one must not confuse the attraction that the required configuration has on the apparent structure of the image with the properties that controlled the formation of that image. The results of Experiment 4 are particularly illustrative in this respect. In a situation in which the preferred dynamics cannot be expressed and in which the environmental dynamics are strongly disrupted, we succeeded in slowing the migration process and temporarily increasing the level of variability, but we did not succeed in modifying the level of image consistency that was reached as soon as the disruption ended. Thus, the migration process has its own dynamic (intrinsic or environmental), independent of the dynamic of the structuring process, even though—as these two dynamics evolve in parallel—their functional independence cannot appear in traditional learning situations. In this light, the level of image accuracy appears less as the result of a cognitive computation as the expression of an emerging process, constrained both by the action of the structuring dynamics that serve to produce a clearer and clearer image and by the intrinsic or environmental dynamics that give content.

Finally, our results show that two processes are simultaneously at play in visuospatial memorization, and, in our opinion, in any memorization process:

The first is a process that mainly acts on image accuracy. Between the real configuration and the memorized configuration, there are differences that decrease with learning but still remain great in the steady state. Using a visual metaphor, one can liken these persistent differences to a "cognitive astigmatism."

The second is a variation process that is independent of accuracy—and thus from the presented figure—and is particularly visible in the steady state when the participant's responses are compared with each other. Among normal and young participants, this dispersion, which leads each element of the configuration to occupy distinct places in time, remains substantial. Again using a visual metaphor, one can liken this mnesic "blur" to nearsightedness (resolution level). However, the simultaneity of these two independent processes—like nearsightedness and astigmatism—has considerable consequences on overall mnesic performance. Indeed, the stability of the image conditions the quality of its accuracy. If the mnesic process is too unstable, it is useless to expect a good level of accuracy and even less so, good learning capabilities.

Inversely, it is just as useless to look for perfect memory reproducibility or a perfect fit between the memory and the percept if at each moment recall leads to an image that is different from the image of the previous moment. One can imagine that with hundreds of trials, one might find two strictly identical reproductions or one reproduction that is strictly identical to the percept. However, this would only be a matter of a discrete phenomenon. It is also important not to confuse the appearance of discrete phenomena with the mental processing of information that itself depends on continuous processes. The spatial and temporal instability of memory appears as the adaptability condition of the system. In a way similar to neural network instability, which offers surprising organization and reorganization capabilities to the nervous system (Meyrard, Simmers, & Moulins, 1991; Weimann, Meyrard, & Marder, 1991), the instability of memory is a reflection, in the behavioral domain, of the participant's ability to deal with the various cognitive disruptions than can occur.

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