Action blindness in response to gradual changes

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ABSTRACT

The goal of this study is to characterize observers' abilities to detect gradual changes and to explore putative dissociations between conscious experience of change and behavioral adaptation to a changing stimulus. We developed a new experimental paradigm in which, on each trial, participants were shown a dot pattern on the screen. Next, the pattern disappeared and participants had to reproduce it. In some conditions, the target pattern was incrementally rotated over successive trials and participants were either informed or not of this change. We analyzed both awareness of the changes and the dynamics of behavioral adaptation, in a way that makes it possible to assess both variability and accuracy as they change over time. Results indicate a dissociation between change awareness and behavioral adaptation to the changes, and support the notion that unconscious representations of visual stimuli are more precise and detailed than previously suggested. We discuss the implications of these results for theories of change detection.

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1. Introduction

Change detection is the apprehension of change in the world around us. Given that the visual world is constantly changing, ability to detect change is a crucial skill in much of our everyday life. However, in spite of observers' mistaken impression that they can detect most visual changes ("change blindness blindness"; Levin, Drivdahl, Momen, & Beck, 2002; Levin, Momen, Drivdahl, & Simons, 2000), the study of change detection has produced striking evidence that observers may remain surprisingly insensitive to changes in the visual scene during an eye movement, film cut or similar masking stimulus, even when these changes are large, recurring, and expected (Rensink, 2002; Rensink, O'Regan, & Clark, 1997; Rensink, 2000; Simons, 2000; Simons & Levin, 1998, 2003). This robust and dramatic phenomenon has been dubbed "change blindness". It may be demonstrated in different ways (for reviews, see Rensink (2000), Simons and Levin (1997)). According to some change blindness theorists (Becker & Pashler, 2002; Levin & Simons, 1997; O'Regan, 1992; O'Regan and Noë, 2001; O'Regan, Rensink, & Clark, 1999; Rensink, 2000, 2002; Rensink, O'Regan, & Clark, 1997; Simons, 1996; Simons & Levin, 1997), the phenomenon is evidence that representations in visual memory are poor and schematic. Detecting a change, indeed, seems to require that both the pre- and post-change information be represented in memory so that comparisons can be made. The prevalence of change blindness suggests that this often does not hold. Congruently, this argument is consistent with earlier evidence for memory distortions, which suggests that observers do not retain complete visual details from one view to the next (French, 1953; Hochberg, 1968; Pashler, 1988; Phillips, 1974; Bridgeman, Hendry, & Stark, 1975; Mack, 1970; McConkie & Zola, 1979; Wallach & Lewis, 1966.

However, other evidence challenges this view. A recent study (Hollingworth & Henderson, 2004) is relevant in this context. The authors used what could be called a "gradual flicker paradigm", that is, an adaptation of the flicker paradigm developed by Rensink, O'Regan, and Clark (1997). In this "gradual flicker paradigm", a natural scene was incrementally changed in

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steps of 1° of visual angle on each display, with each display separated from the next one by a brief blank screen (1500 ms). Participants were instructed to press a button if they had noticed the scene change. The results indicated that half of the participants remained unaware of the change up to a dramatic rotation of 48°. However, when a shift back to the original scene was produced after a cumulated rotation of 20° or 30° that had so far remained undetected, most subjects could then clearly see the change. Authors concluded that visual memory had been updated, albeit in the absence of awareness. Indeed, if visual memory had not been updated at all, participants would not have been able to detect the change when presented anew with the original display. These results clearly challenge the idea that change blindness arises from a failure to maintain relevant information in memory (see also, Simons, 2000; Simons & Rensink, 2005).

More generally, such findings raise the possibility that changes concerning visual stimuli and of which one remains unaware are nevertheless represented in visual memory. For example, visuomotor systems can be controlled by stimuli that are not seen consciously (Bridgeman et al., 1975; Fourneret & Jeannerod, 1998), familiarity of unrecognized faces can influence skin conductance (Bauer, 1984), and forced-choice guessing of unseen stimuli can be better than chance (Fernandez-Duque & Thornton, 2000; Laloyaux, Destrebecqz, & Cleeremans, 2006; Merikle & Daneman, 1998). Recent findings about implicit change detection (Fernandez-Duque, Grossi, Thornton, & Neville, 2003; Fernandez-Duque & Thornton, 2000, 2003; Laloyaux et al., 2006; Laloyaux, Devue, Doyen, David, & Cleeremans, 2008; Thornton & Fernandez-Duque, 2000, 2002), in particular have suggested the continued existence of visual information that nevertheless appears to remain inaccessible to the mechanisms underlying conscious change detection. Thus, although it was originally assumed that—at least for human observers—the use of visual input must always be accompanied by a conscious visual experience of the relevant objects or events, recent results have shown that this is not always the case. A recent study by Laloyaux et al. (2006), in which the authors improved on the original design first described by Thornton and Fernandez-Duque (2000), makes this point particularly clear. The paradigm involves exposing participants to circular arrays of 8 rectangles, each of which can be oriented vertically or horizontally. On each trial, participants first see an array of such items for 250 ms. This is followed by a blank screen, shown again for 250 ms, and then by a second array of rectangles that is either identical to the first, or in which one item has changed orientation. This is then immediately followed by a third display, shown for only 20 ms, in which one of the items is now colored white. Participants have to (1) indicate whether they have perceived a change over the first two displays, and (2) indicate the orientation of the white rectangle shown on the third screen. The main result of these experiments was that accuracy in the orientation detection task was facilitated by congruent changes over the first two displays (i.e., changes that ended in the orientation of the white rectangle) regardless of whether the change had occurred at the same location, and, most importantly, regardless of whether participants had reported awareness of the change or not. Thus, changes can influence subsequent performance, suggesting that people retain detailed visual information about the change even when unable to report having detected their occurrence.

At the same time, numerous recent studies have addressed the relationships between subjective experience of a stimulus and its neural correlates in an attempt to elucidate the neural bases of conscious awareness. Using different brain imaging methods, several studies (Beck, Rees, Frith, & Lavie, 2001; Fernandez-Duque et al., 2003; Haynes & Rees, 2005) have shown that a stimulus that is not perceived consciously nevertheless produces brain activation similar to that elicited by the same stimulus when perceived consciously. To sum up, it appears that our brains "know more than we can tell" (Nisbett & Wilson, 1977), and that nonconsciously perceived stimuli can nevertheless be represented in memory and influence subsequent behavior.

This claim also receives an echo in the field of the motor control. Indeed, studies of motor control (Day & Brown, 2001; Fourneret & Jeannerod, 1998; Goodale, Pelisson, & Prablanc, 1986; Desmurget et al., 1999; Varraine, Bonnard, & Pailhous, 2002) clearly support the idea of implicit sensitivity to change. A study conducted by Fourneret and Jeannerod (1998) provides the most elegant example in this respect. Participants were asked to perform reaching movements. By giving false visual feedback about the trajectory of hand movements, Fourneret and Jeannerod demonstrated that subjects (who could not see their hand) were nevertheless able to voluntary achieve the desired result of drawing a straight line on a computer screen. The necessary corrective movements were produced in spite of the fact that subjects remained unaware of having produced them, at least so long as the corrections remained under a certain (but surprisingly large) threshold. Such findings confirm that changes in visual input can influence subsequent behavior in such a way that participants fail to become aware either of the change itself or of the corrective movements they perform in response to it (for further discussion on these points with respect to action awareness, see Johnson & Haggard, 2005; Cleeremans & Sarrazin, 2007). Thus, under certain conditions, both perception (change detection) and action (behavioral adaptation) may occur outside of awareness.

These and other findings leave open important questions, however. First, how does implicit detection of change differ from explicit detection of change? Given the possibility that observers may exhibit sensitivity to changes without awareness, an important issue is to determine how the mechanisms involved in implicit change detection are related to the mechanisms that subtend explicit change detection. More specifically, the issue is to determine if subsequent behavioral adaptation to the change differs or not in the presence of conscious experience of the change. Second, what is represented, if anything, when a change remains undetected? Given the growing body of studies that suggest that the brain can represent and process some information outside the focus of attention or below the level of awareness (see for instance Debner & Jacoby, 1994; Destrebecqz & Cleeremans, 2001; Dienes & Perner, 1999; Greenwald, Abrams, Naccache, & Dehaene, 2003; Merikle, Smilek, & Eastwood, 2001), it is clear that unconscious visual stimuli are represented in memory. If so, it becomes important to document the various types of information that are preserved, the subsets thereof that can be accessed by each group of change-detection mechanisms, and the reasons for these limits. Third, what role does memory play in change blindness? Accurate

visual memory representations of pre-change stimuli must be encoded and maintained in memory for change detection to occur (see Simons (2000) for review). However, as underlined by Simons, although change blindness can arise from a failure to maintain relevant information, it can also arise from a failure to access or compare the relevant representations (see e.g., Mitroff, Simons, & Levin, 2004; Simons, 2000). If so, a key concern in understanding the mechanisms involved in change blindness is to determine how representations of change evolve in memory in the absence of conscious experience of this change.

In this paper, we have attempted to explore these different questions by using an adaptation of the gradual flicker paradigm proposed by Hollingworth and Henderson (2004). On each trial, participants were first shown a dot pattern on the screen. Next, the pattern disappeared and participants had to reproduce it. In some conditions, the target pattern was incrementally rotated over successive trials and participants were either informed or not of this change. We measured both awareness of the change (verbal reports) and behavioral adaptation to this change (reproduction task). With respect to the paradigm proposed by Hollingworth and Henderson from which it is inspired, our paradigm presents several advantages. First, the reproduction task makes it possible to better characterize the details of the memory traces retained by participants. Further, combined with subjective measures of change detection, the objective, behavioral measure made possible by the reproduction task allowed us to study awareness of action, and more generally, the relationship between perception and action. Finally, because verbal reports and action reproductions were collected on each trial (Experiment 2), we have access to both the subjective and objective dynamics of action awareness. Such trial-by-trial measures thus offer a convincing way of documenting possible dissociations between subjective experience and action.

2. Experiment 1

The questions explored in this first experiment were (1) whether observers can be sensitive to changes that they have failed to perceive consciously and (2) whether such overlooked changes can nevertheless influence subsequent behavior. To address these issues, we asked participants to memorize and reproduce dot patterns several times in succession. Specifically, on each trial, a dot pattern (see Fig. 1) was shown for 5 s and then disappeared, leaving the screen blank. Participants were then asked to reconstruct the dot pattern by repeatedly dragging dots from a pool using a computer mouse, and by repositioning them in their original location. In some conditions, the target pattern was rotated by a small increment over successive trials. Participants were either informed or not that such changes could occur. To find out whether such changes influence behavior, we measured different aspects of participants' reproductions (i.e., accuracy, variability, rotation). At the same time, we evaluated participants' conscious experience of change through verbal reports obtained at the end of the experiment. One possible outcome of comparisons between these different measures is the finding of a direct relationship between conscious experience of change and behavioral adaptation to this change. If so, in cases where the change was not detected explicitly, we should fail to observe rotations in participants' reproductions. Accuracy and variability should further be comparable to what is observed when no change occurs. In contrast, conscious experience of change should result in participants rotating their successive reproductions as they attempt to match the rotated visual displays. This should also be reflected by changes in accuracy and variability compared to conditions under which no change occurs. The second possibility is the finding of a dissociation between conscious experience of change and behavioral adaptation to this change. If so, we might expect that the same pattern of behavioral adaptation (rotation of participants' reproductions, decreased accuracy and increased variability) will occur regardless of whether participants report awareness of the change.
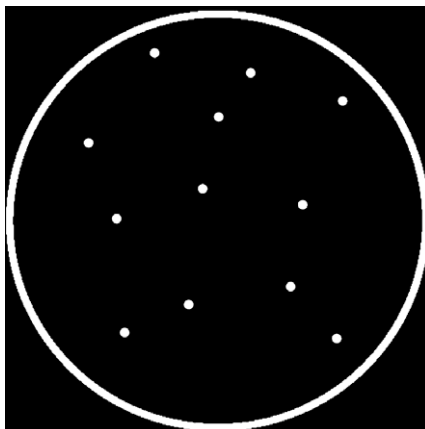

Fig. 1. Target configuration presented on the first trial.

2.1. Method

2.1.1. Participants

45 students (28 women and 17 men) from the Université Libre de Bruxelles participated in the experiment for course credit. All had normal or corrected-to-normal vision and were naïve as to the hypothesis under investigation. Their mean age was 22 (range = 19–24 years). The 45 participants were randomly assigned to one of the three experimental conditions, so constituting three groups of 15 participants.

2.1.2. Material

Stimulus presentation and data acquisition were conducted using a PC computer running Labview 7.1 (http://www.ni.-com/labview/) for Windows 2000 and connected to a 17-in. 100-Hz CRT monitor. The monitor was located 1.70 m from the participant, so that the configuration appeared in perifoveal vision (i.e., without necessitating head movement).

2.1.3. Stimuli

The stimulus display (see Fig. 1) consisted of a circle (28 cm in diameter) containing a pattern of dots (each 0.4 cm in diameter), presented against a black background. The dot pattern was composed of 12 dots.

2.1.4. Procedure

Participants worked individually. The initial display was presented for 5 s, and participants were told to memorize this stimulus. After the 5 s had elapsed, the configuration disappeared from the screen and was replaced by an empty circle and, on the right upper side of the screen, by a dot that participants could select and drag. Participants' task was to reproduce the seen configuration as accurately as possible. Using the computer mouse, they had to reposition each dot on the screen so as to reconstruct the memorized configuration. To do so, they clicked on the dot situated on the right upper side of the screen and dragged it to the desired location. They were given as much time as needed to perform the task and were allowed to adjust their answers by moving the mouse from one location to another before clicking. However, after creating each dot via a mouse click, they could not go back and modify their decision. At the end of each trial, the reproduced configuration was removed, and the next trial began immediately.

The experiment involved three conditions. In the first, "no change" condition, each participant performed the task 16 times. The visual display was identical over the 16 trials, and the participant performed the reproduction task on each of these 16 trials. This condition is therefore a control condition that makes it possible to assess participants' accuracy and variability when successively reproducing the same unchanging dot pattern on 16 successive occasions. The other two conditions, respectively called the "told change" and "told no change" conditions, were characterized by the occurrence of changes in the successive stimuli. Here again, each participant performed the reproduction task 16 times. However, on each trial, the visual display to be reproduced was incrementally rotated by 2°. In other words, we used the "incremental scene rotation" introduced by Hollingworth and Henderson (2004), resulting in a final and very salient difference of 30° between the initial and final displays (see Fig. 2). In the "told no change" condition, participants were given the same instructions as in the "no change" condition, that is, they were told that would see the same stimulus appear 16 times and that they simply were to reproduce this stimulus as accurately as possible on each presentation. Participants were thus unwittingly exposed to a changing stimulus in this condition. In the "told change" condition, by contrast, participants were informed of the fact "that a different stimulus would occur on each trial". In this condition, participants therefore had full knowledge that the material would contain changes, but were not given specific information about the nature of theses changes.
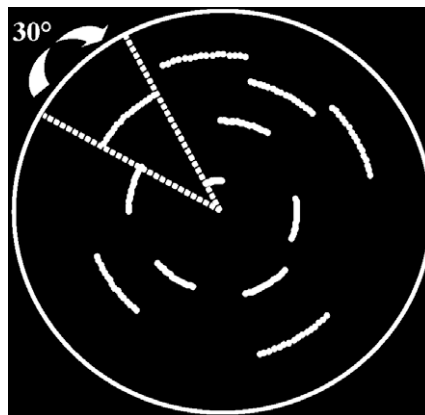

Fig. 2. Evolution of the target configuration during the experiment with an incremental scene rotation from the left to the right resulting in a final 30° change of the initial display.

At the end of the 16th trial, participants in all three conditions were asked whether they had noticed "anything unusual" and "anything that had changed" in the stimuli. If participants reported any sense of anything "strange" or anything "having changed", we considered them as being aware of the change, thus using a very conservative criterion to attribute lack of awareness.

This verbal report was followed by a recognition task in which participants were asked to select the stimulus or the stimuli they had been exposed to among five possible stimuli, and to rate their confidence in their decision on a scale ranging from 0 ("Not very confident") to 3 ("Very confident"). In the "told no change" and "told change" conditions, amongst the five stimuli presented, three had actually been presented during the experiments (on trials 1, 8 and 16, that is, on the first trial, on the "middle" trial and on the final trial). The two other stimuli were distractors that had not been presented. In the "no change" condition, the same five stimuli were presented to participants, but only one of them had actually been presented during the experiment, with the four others acting as distractors. The position of each stimulus during this recognition task was randomly assigned and counterbalanced between participants.

Finally, participants performed two additional trials and were then asked again whether they had noticed any unusual features or changes during these final two trials. In the "no change" condition, the same visual display was presented in the two trials. In the "told no change" and "told change" conditions, the visual display presented during the first trial corresponded to the initial display, whereas the visual display presented during the second trial corresponded to the initial display rotated by 30°. Altogether, the experiment took approximately 40 min to complete in each condition.

2.1.5. Data processing

This design made it possible to combine the classical methodology of verbal reports and forced-choice task with behavioral measures. At the behavioral level, three distinct measures were computed. By comparing the produced configurations, we focused on accuracy, that is, the discrepancy between each response and the target configuration (the configuration to be learned) and on variability, that is, the difference between each response and the immediately preceding response. Both accuracy and variability were thus computed by calculating the distance between two dot patterns—the target and the response in the case of accuracy; two successive responses in the case of variability. This way of proceeding further gives us information about how both measures change over time, that is, over the course of the experiment.

To compare the configurations, we analyzed the data with a bidimensional regression algorithm (see Giraudo & Pailhous (1994, 1999) concerning details on the method) that was initially developed by Tobler (1976, 1977, 1978a, 1978b). This algorithm uses Euclidean transformations (e.g., translation, rotation, and scale change) to minimize the discrepancy between pairs of configurations. The algorithm is conceptually similar to the program used by Kosslyn, Pick, and Fariello (1974) and to the calculations performed by Pani, Zhou, and Friend (1997). It provides a measure of the mean discrepancy between two configurations (root-mean-square error, RMSE), as well as a measure 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 necessary lead to a reduction in the value of each local discrepancy.

Finally, we also computed the rotation of participants' successive reproductions. If the first two measures ("image accuracy" and "image variability") correspond to a behavioral measure of sensitivity to the change, this third measure allowed us to measure mnesic adaptation to the change. Indeed, if the representation in memory is updated during the rotation of the stimulus, rotation should also be observed in participants' reproductions.

2.2. Results

2.2.1. Verbal reports

Verbal reports (see Fig. 3) were used to measure subjective experience of change. In the "no change" condition, participants reported no awareness of change, neither after the 15 reproductions nor after the final two trials. This was of course expected, since the displays failed to contain any change. In the "told no change" condition, four out of 15 participants reported awareness of change. Thus, 11 out of 15 (74%) participants failed to detect any change after gradual exposure to a global scene rotation of 30°. Of the four participants who had detected a change, one reported "a scene rotation" and three reported "a global change of the visual display". When the same change (30°) was presented abruptly over the final two trials, all participants reported awareness: Three reported a scene rotation and 12 reported a radical change of the visual display (i.e., a change in the structure of the stimulus). In the "told change" condition, 100% of participants reported the presence of change in the stimulus and also the presence of a common structure between trials whatever the nature of the change (gradual or abrupt—over the final two trials). For both gradual and abrupt changes, two participants reported the presence of a scene rotation and 13 reported the presence of a global change in the visual display (slight variations of the same structure). In other words and as expected, participants were more aware of the presence of a change when instructions had oriented them to that change. However, most were unable to clearly identify the nature of the change (that is, a rotation).
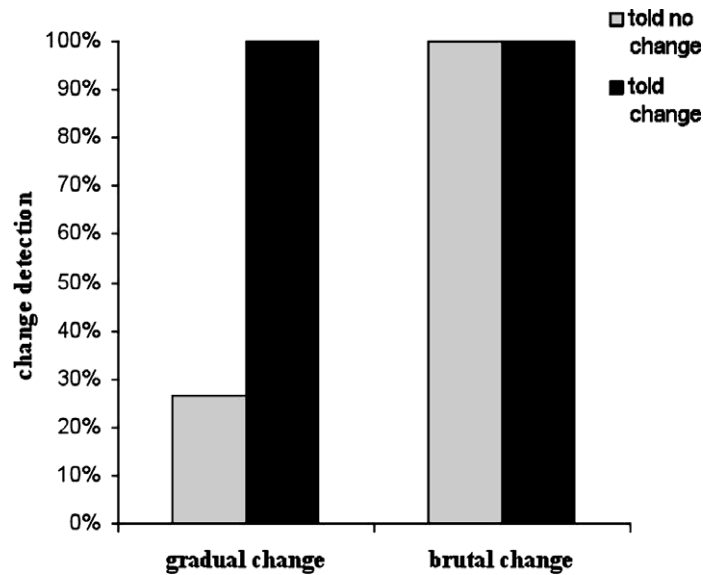
Fig. 3. Percentage of noticed changes for the conditions "told no change" in grey and "told change" in black. Large change blindness appears in the condition "told no change".

2.2.2. Recognition task and confidence judgments

After participants had been probed about their awareness of the changes, they were asked to perform a recognition task in which they had to select the visual display they had had been presented with during the first 16 trials amongst five stimuli. In the "no change" condition, one stimulus was the target and the other four stimuli were distractors. In the "told no change" and "told change" conditions, three stimuli had actually been presented during the main task (T1 at trial 1, T8 at trial 8 and T16 at trial 16) and two were distractors. After they had made their choice, participants were then finally asked to report on their level of confidence in their decision, using a scale ranging from 0 ("Not very confident") to 3 ("Very confident").

In the "no change" condition, all participants selected the correct item, which demonstrates that accurate memory for the specific stimulus participants had been exposed to is possible. Mean level of confidence was 2.40 (SD = 0.33) (see Fig. 4).

In the "told no change" condition, amongst the 11 participants who had failed to detect changes, three selected T1, four selected T8 and four others selected T16 (see Fig. 5). The overall level of confidence was 2.22 (SD = 0.47). As expected, all participants reported only one stimulus as perceived and no participant selected one of the distractors. In contrast, amongst the four participants who had detected a change, all participants selected T1, T8 and T16 as perceived during the experiment.
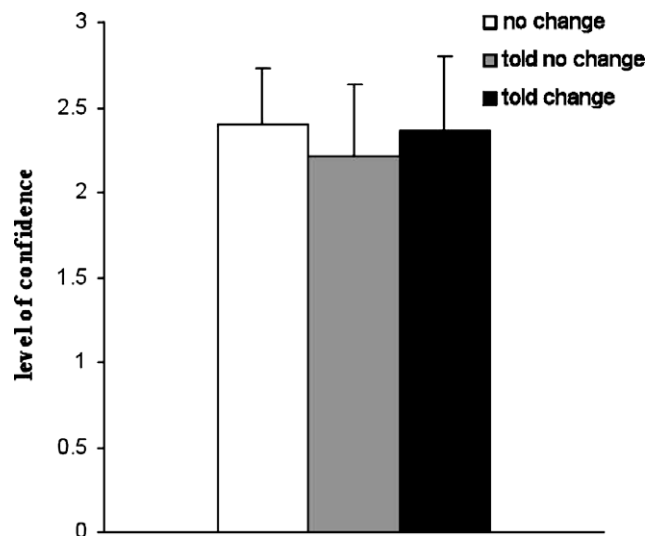

Fig. 4. Average confidence rating (0 = 'Not very confident'; 3 = 'Very confident') as a function of condition ("no change", "told no change" and "told change"). A high level of confidence appears in the three conditions.
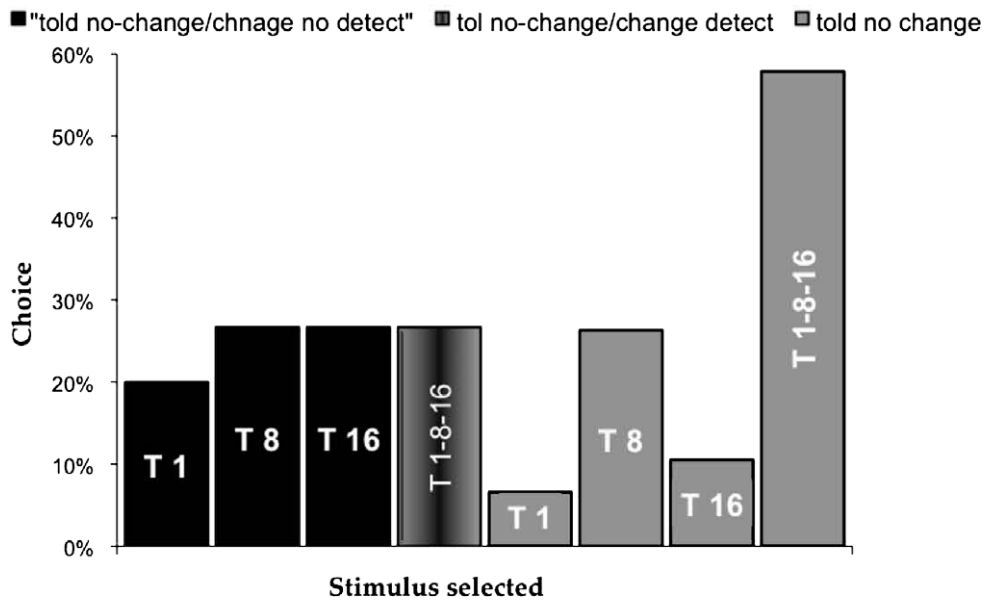
Fig. 5. Stimulus identified as target during the identification task for the "told no change" and "told change" conditions. Amongst the five stimuli presented, three had actually been presented during the experiments (T1, T8 and T16) and two were distractors. 100% of participants reported one of the target really presented during the experiment. However, if participants who did not report the presence of change identified only one target, a majority of participants who reported the presence of change identified the three targets (T1, T8 and T16) as perceived.

Their mean level of confidence was 2.37 (SD = 0.62). In term of level of confidence, no statistical difference (two-tailed t test) was observed between the two groups, with $t(13) = 0.50$, n.s. Moreover, no statistical difference was observed between the "told no change" and "told change" conditions, with $t(28) = 0.92$, n.s.

In the "told change" condition, a majority (eight participants) selected the three stimuli (T1, T8 and T16) as seen during the experiment. This was of course expected, since all participants had been told the stimulus would be changing. Amongst the other participants, one selected T1, four selected T8, and two selected T16 (see Fig. 5). No statistical difference appeared between the response distributions of participants in the "told no change" and "told change" conditions, $\chi^2(3) = 3$, n.s. However, results observed in the "told no change" condition suggest that participants were more efficient in the recognition task when awareness of the change had been reported. In term of level of confidence, the mean level of confidence for the "told change" condition was 2.41 (SD = 0.42). No statistical difference was observed between this level of confidence and the mean level of confidence observed in the "no change" and "told no change" conditions, with $F(2, 42) = 0.595$, n.s. These results suggest that participants exhibited the same level of confidence in their choice regardless of the presence of change and regardless of whether they had reported having perceived it.
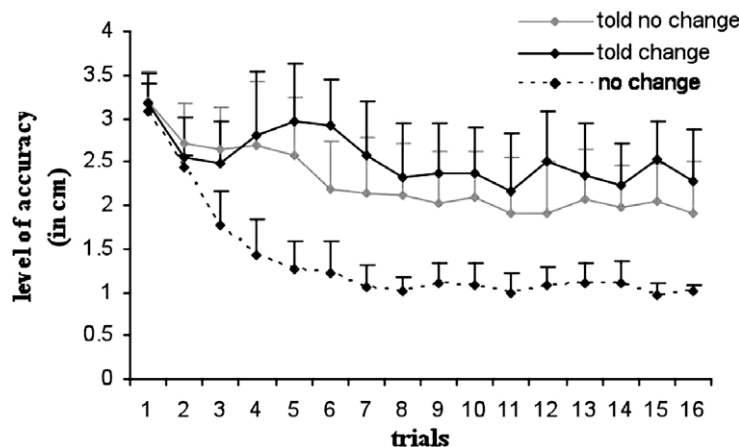

Fig. 6. Evolution of the mean value of configuration accuracy for the three conditions. Change in the stimulus leads to a decrease in response accuracy.

2.2.3. Behavioral measures

Accuracy (see Fig. 6) was used to study the evolution of the distance between the target configuration and each response configuration across trials (i.e., over time). In the two changing conditions, accuracy was measured relative to the specific stimulus that was presented on a given trial. Large values indicate large distances between the two configurations. In contrast, the lower the computed value, the smaller the discrepancy between the configurations. Therefore, the curve shows increases and decreases in the discrepancy between two configurations. Because the algorithm we used removed Euclidean transformations, in particular rotation, our measure of accuracy is not informative about the relative rotation of responses in reference to the target. In other words, if the only difference between the target and the response was a rotation, the discrepancy would be equal to 0.0 Therefore, our measure of accuracy only revealed angular and distance ratio discrepancies between the target and the subject responses. The value was first computed for each participant and then averaged to produce a mean value. The significance level for those means was less than or equal to .01.

Given that we failed to observe a statistical difference between participants who had reported change and those who had not in the "told no change" condition for both accuracy ($t(30) = 0.75$, *n.s.*) and variability ($t(28) = 0.02$, *n.s.),* the rest of the analysis was performed on the entire data set. The results show that mean accuracy on the first trial was 3.07 cm (SD = 0.33 cm), 3.19 cm (SD = 0.34 cm) and 3.19 cm (SD = 0.35 cm) for the "no change", "told no change" and "told change" conditions respectively. No statistical difference was observed between conditions, with $F(2, 35) = 0.41$, *n.s.*

We then explored the dynamics of accuracy over the entire course of the experiment. To do so, we defined a "learning phase" and a "steady state phase" by using the procedure developed by Pailhous and Bonnard (1992) and used in previous studies (Giraudo & Pailhous, 1999; Sarrazin, Giraudo, Pailhous, & Bootsma, 2004; Sarrazin, Giraudo, & Pittenger, 2005; Berberian, Sarrazin, & Giraudo, 2007; Sarrazin, Tonnelier, Berberian, & Giraudo, 2008). The learning phase was considered to be complete when performance had stabilized, that is, when there was no further improvement in accuracy over several trials.

In each condition participants were in the learning phase from the first trial onwards, as the produced response configurations became progressively closer and closer to the stimulus to be learned. Starting from the 4th trial in the "no change" condition, from the 8th trial in the "told change" condition and from the 9th trial in the "told no change" condition, participants were then in a steady state phase, as their responses did not get closer and closer to the target anymore. The maximum level of accuracy was achieved with a gain of 2.00 cm, 1.22 cm, and 1.10 cm respectively for the "no change", "told no change" and "told change" conditions, and the subsequent trials on which participants still saw the target before each response were not useful in improving accuracy. At this point, the mean level of accuracy was 1.06 cm (SD = 0.20 cm), 1.99 cm (SD = 0.54 cm), 2.12 cm (SD = 0.62 cm) respectively for the "no change", "told no change" and "told change" conditions. The results indicate that accuracy differed across conditions, $F(2324) = 104.22$, $p < .01$. Post hoc analysis (Newman–Keuls) revealed that participants were significantly more accurate in the "no change" condition than in the two other conditions ($p < .01$). In other words, distance to target in the steady state phase remains higher in the presence of change in the stimulus.

To study how participants' reproductions changed over time independently of the target, we assessed variability by computing the distance between successive participant productions, comparing responses at time t with responses at time $t + 1$ (see Fig. 7). As for accuracy, the algorithm removed Euclidean transformations, in particular rotation. Therefore, the variability measure only revealed angular and distance ratio discrepancies between successive participant responses. For example, if a participant had reproduced exactly the same configuration on each trial, but for a 2° change in rotation, variability should be equal to 0. In other words, our measure of variability was not sensitive to changes in rotation.

The results showed that for the first trial the mean value of variability was 2.59 cm (SD = 0.30 cm), 2.65 cm (SD = 0.64 cm) and 2.69 cm (SD = 0.53 cm) respectively for the "no change", "told no change" and "told change" condition. At this point, no
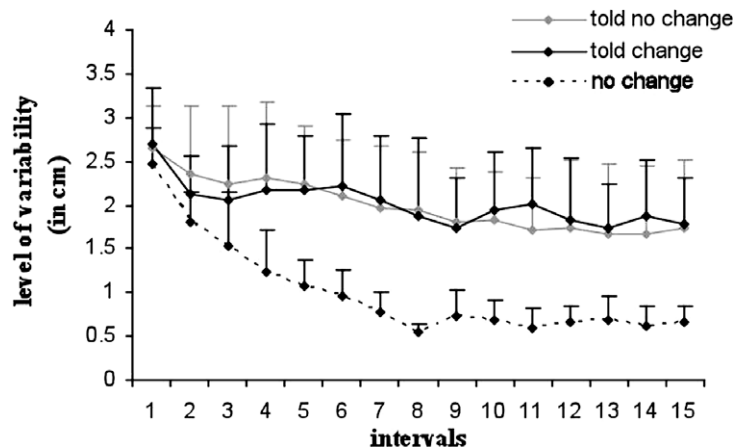

Fig. 7. Evolution of the mean value of configuration variability for the three conditions. Change in the stimulus leads to an increase of response variability.

statistical difference was observed between conditions with $F(2, 35) = 0.09$, *n.s.* We then explored the dynamics of variability in the same manner as for accuracy.

In each condition, the distance between successive responses became smaller and smaller over the first trials. Starting from the 6th interval in the "no change" condition, the 8th interval in the "told change" condition and the 11th interval in the "told no change" condition, the results showed that the distance between successive responses stopped changing, suggesting that participants had reached a steady state. The maximum level of image resolution (i.e., the level of variability in the steady state) was achieved with a gain of 1.89 cm, 0.85 cm, and 0.96 cm respectively for the "no change", "told no change" and "told change" conditions. At this point, the mean level of variability was 0.66 cm (SD = 0.21 cm) for the "no change" condition, 1.70 cm (SD = 0.59 cm) for the "told no change" condition and 1.74 cm (SD = 0.57 cm) for the "told change" condition. A one-way ANOVA showed that variability differed across conditions, $F(2241) = 106.76$, $p < .01$. Post hoc analyses (Newman–Keuls) revealed that the "no change" condition elicited significantly less variability than the two other conditions ($p < .01$). In other words, the distance between successive reproductions in the steady state increased in presence of change in the stimulus.

Because our measures of accuracy and of variability were not informative about rotation, we also computed a mean rotation value for the configuration (see Fig. 8). The rotation measure was used to study the evolution of the rotation between two configurations consecutively produced by the participants, independently of the target. Positive values indicate a rotation of participants' reproductions congruent with the stimulus rotation, whereas negative values indicate rotations of the participants' reproductions that are incongruent with the stimulus rotation.

The results showed that the mean rotation value was 0.56° (SD = 3.46°) for the "no change" condition, 22.99° (SD = 5.87°) for the "told no change" condition and 19.98° (SD = 5.85°) for the "told change" condition. A t test performed on the rotation measure compared with random performance (rotation = 0°) showed that no significant rotation was observed in the "no change" condition, with $t(14) = 0.63$, *n.s.* This was of course expected, since the displays failed to contain any change. In contrast, we observed significant rotation in the "told no change" condition, with $t(14) = 15.03$, $p < .01$, like in the "told change" condition, with $t(14) = 13.22$, $p < .01$, which suggests the presence of congruent rotation of the participants reproduction in these two conditions. Finally, no difference was observed between participants who had reported the presence of a change (four in the "told no change" condition and 15 in the "told change condition" and those who had reported no change (11 in the "told no change" condition) with $t(28) = 0.34$, *n.s.* In other words, participants exhibited the same level of rotation in their productions regardless of whether they were aware of the presence of a change in the stimulus or not.

2.3. Discussion

The main results of this first experiment were as follows:

(1) Participants can be dramatically blind to a change when the change is gradual. Specifically, in the "told no change" condition, a large majority of participants failed to perceive the change even after a stimulus rotation of 30°. Change blindness was confirmed by the recognition task and the measure of confidence. Indeed, in the "told no change" condition, participants selected only one target when they had reported no change in the stimulus and demonstrated a high level of confidence in their choice. This result suggests that no "feeling of change" was present when participants reported being unaware of the change. This result is consistent with prior research demonstrating that incremental changes may be particularly difficult to notice explicitly (Hollingworth & Henderson, 2004; Simons, Franconeri, & Reimer, 2000). Moreover, as already shown by Hollingworth and Henderson (2004), the same change presented abruptly was clearly detected by all participants.

Considering separately the "told no change" and "told change" conditions, the results showed that conscious experience of the change was influenced by instructions. Indeed, for the same physical magnitude of change, a different level of awareness was observed as a function of the instructions given to participants, with large change blindness in the "told no change" condition and a high level of change detection in the "told change" condition. This result was consistent with a large number of studies that have found a strong relationship between expectation of change and conscious perception of change (see for example Rensink, 2002; Simons & Levin, 1997; Simons & Rensink, 2005; Triesch, Ballard, Hayhoe, & Sullivan, 2003).

(2) Our behavioral results suggest that sensitivity to visual changes occurs even in absence of conscious experience of the changes. Specifically, during the first trials, we observe a short structuring phase (characterized by an improvement in both accuracy and variability) despite the presence of change in the stimulus. These results suggest that changes are initially undetected since both accuracy and variability improved in the same way with or without change. However, after this initial phase, the results show that both distance to target (accuracy) and distance between successive reproductions (variability) were larger in the presence of change than in the "no change" condition. This increase of image variability and the correlated decrease in accuracy in the presence of change in the stimulus suggests that participants are sensitive to the change regardless of their ability to report such changes when probed explicitly. Because participants were not conscious of this change in the "told no change" condition, we can thus speak of "implicit change sensitivity". Moreover, the evolution of both image accuracy and image variability were identical regardless of whether participants had reported the presence of change or not. This result suggests that change sensitivity is dissociated from
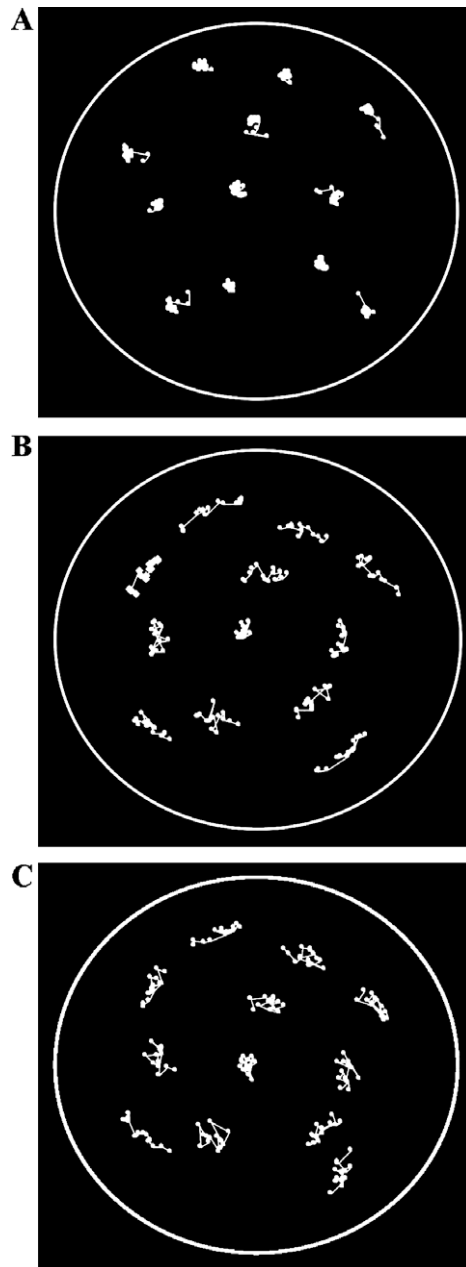
Fig. 8. Average reproduction over time in the conditions "no change" (a), "told no change" (b), and "told change" (c). A rotation of the reproduction was observed in the conditions "told no change" and "told change".

change awareness. In this respect, our results are consistent with a large body of research on implicit change detection (Fernandez-Duque & Thornton, 2000, 2003; Fernandez-Duque et al., 2003; Hollingworth & Henderson, 2004; Laloyaux et al., 2008; Mitroff & Simons, 2002).

(3) Finally, our results are suggestive that participants' behavior reflects unconscious adaptation to change. Indeed, we observed dissociations between verbal reports of change and behavioral adaptation, marked by the presence of rotation in participants' reproductions. Such a finding is congruent with the notion of action blindness developed in motor control studies (Day & Brown, 2001; Desmurget et al., 1999; Fourneret & Jeannerod, 1998; Goodale et al., 1986; Varraine et al., 2002).

Our inferences are dependent on the assumption that verbal reports constitute a good indicator of the subjective contents of visual awareness. One could argue, however, that our post-experimental test did not compel participants to report the

actual conscious information on which their performance was based. In particular, verbal reports may lack sufficient sensitivity (i.e., Shanks & St John, 1994). To address this important issue, we conducted a second experiment with the goal of improving our measure of awareness so as to provide a more stringent assessment of the extent to which people are conscious of each change (see Cheesman & Merikle, 1984; Kunimoto, Miller, & Pashler, 2001).

3. Experiment 2

Experiment 1 indicates that change sensitivity can occur in the absence of conscious experience of the change. However, this interpretation rests on the assumption that verbal reports are sufficiently sensitive. However, if verbal reports are generally accepted as the most direct manner through which to assess awareness, their limits have also been well documented. For example, Merikle and Reingold (1990) have insisted that subjective measures of unconscious perception must be interpreted with caution because they depend on participant's interpretation of the task instructions. For instance, participants might give a more liberal interpretation to the term "guess" than the experimenter, and therefore tend to claim that they were guessing while in fact basing their responding on low confidence, fragmentary, but nevertheless conscious knowledge (see also Cheesman & Merikle, 1984).

To rule out this potential bias, Kunimoto et al. (2001) introduced a different way of assessing awareness of visual changes by proposing to combine a trial-to-trial measure of awareness and a subjective confidence rating to the change detection report. As argued by Laloyaux and collaborators (Laloyaux et al., 2006, see also Dienes & Berry, 1997), this method allows one to better dissociate perceptual sensitivity from awareness. Indeed, if participants can discriminate between different kinds of stimuli better that chance would predict while their confidence ratings are not predictive of their performance, this would constitute good evidence that change sensitivity depends on information that people remain unaware of.

3.1. Method

3.1.1. Participants

15 students (nine women and six men) from the Université Libre de Bruxelles participated in the experiment for course credit. All had normal or corrected-to-normal vision and were naïve as to the hypothesis under investigation. Their mean age was 20 (range = 19–23 years).

3.1.2. Material

The material was identical to that in the first experiment.

3.1.3. Stimuli

The stimuli were identical to that in the first experiment.

3.1.4. Procedure

As in the first experiment, the initial display was presented for 5 s, and participants were told to memorize this stimulus. After the 5 s had elapsed, the configuration disappeared from the screen and was replaced by an empty circle and, on the right upper side of the screen, by a dot. Participants' task was identical to the first experiment.

In contrast to the first experiment, each participant performed the task 30 times instead of 15 times. In 50% of trials, the visual display was incrementally rotated by 2° as in the first experiment. However, in the remaining 50% of the trials, the stimulus was identical from one trial to the next. Three different orders of alternation between changing and unchanging targets were randomly defined and five participants were assigned to each sequence. Finally, the global amount of change between the initial display and the final display was identical to the first experiment, that is, 30°.

Concerning the instructions given to participants, observers were asked to memorize a visual display of dots while being told that a change could occur "sometimes".

On each trial, verbal reports were recorded in two steps. Participants were first asked if they had seen a change in the stimulus. Second, participants were asked about how confident they were in their judgments. Finally, at the end of the 30th trial, participants were asked about the nature of the perceived change. This design thus made it possible to combine a trial-to-trial assessment of change awareness with confidence judgments. The experiment took approximatively 55 min to complete.

3.1.5. Data processing

Data processing was identical with that in the first experiment.

3.2. Results

3.2.1. Verbal reports

After each reproduction, verbal reports (see Fig. 9) were used to measure the subjective experience of change. The results showed that the global rate of detection was 28% (SD = 6.7%). However, in 50% of trials, no change was present in the stim-
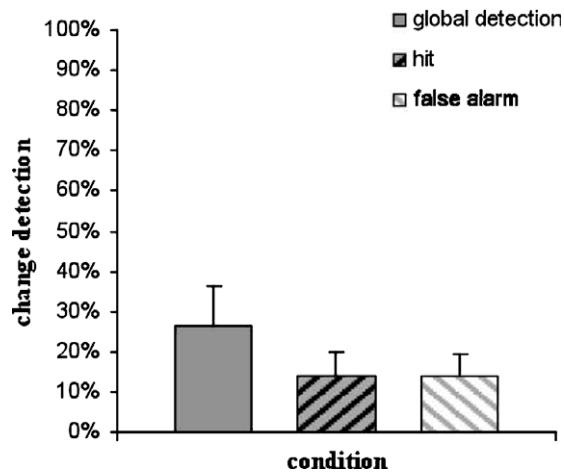
Fig. 9. Percentage of noticed changes as a function of the presence of actual changes in the stimulus. Surprisingly, changes were noticed as often in presence or in the absence of actual changes in the stimulus.

ulus. Thus, we distinguish cases where participants reported a change when a change was indeed present (hits) and cases where participants reported a change but no change was present (false alarms). The average hit rate was 14% (SD = 5.8%) and the false alarm rate was also 14% (SD = 5.4%), yielding an average d' of 0.02 (average of all the individual d' values). A t test performed on d' compared with random performance ($d' = 0$) showed that participants were not able to discriminate between change and no change trials, $t(14) = 0.26$. In addition, we observed that participants exhibited a tendency to report "no change" regardless of the presence of change in the visual display, with $t(28) = 14.29$, $p < .01$ in the absence of change and $t(28) = 12.65$, $p < .01$ in the presence of change. Finally, end-of-experiment reports concerning the identity of the change revealed that all participants reported the presence of some dots that moved in time, but none reported the presence of a rotation of the visual display. As expected, these results indicate that participants are rather poor at detecting changes in this situation, even when explicitly instructed to do so and even when probed on every trial.

3.2.2. Confidence judgements

As explained previously, verbal reports could underestimate the contents of conscious experience. For instance, participants who fail to report the experience of change might do so not because they have failed to detect the change, but simply because they have very low confidence in their perception and use a conservative criterion. We thus attempted to enrich our measures of awareness by asking participants to report on the confidence with which they make their change detection decisions (see Fig. 10). Such a procedure has been previously used in the domains of subliminal perception (Cheesman &
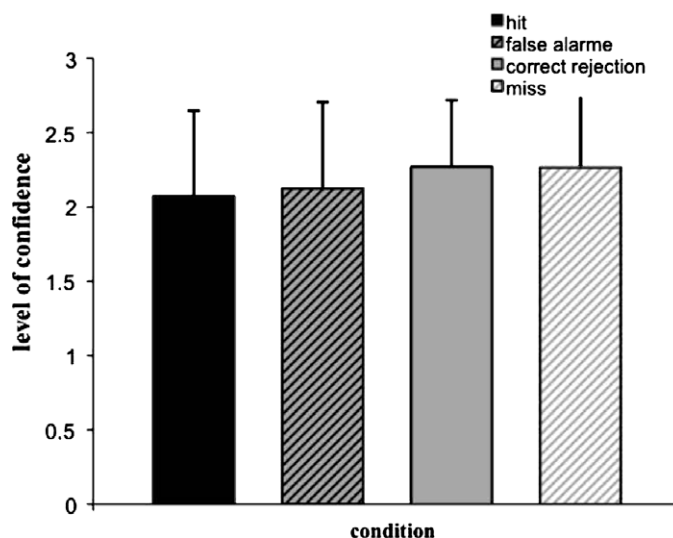

Fig. 10. Average confidence rating (0 = 'Not very confident'; 3 = 'Very confident') as a function of the condition. A high level of confidence appears in the four conditions.

Merkle, 1984) and implicit learning (Destrebecqz & Cleeremans, 2003; Dienes & Berry, 1997; Shanks & St John, 1994) and consists in asking participants to rate on a graded scale, from guess (0) to certain (3), how confident they were in their response. As suggested by Kunimoto et al. (2001), truly implicit processes should be accompanied by high level of confidence.

The average confidence rating was 2.24 (SD = 0.48), that is, a high level of confidence (between "almost sure" and "certain"). We observed that the mean level of confidence was 2.07 (SD = 0.57) in the case of hits (HIT), 2.12 (SD = 0.58) in the case of false alarms (FA), 2.27 (SD = 0.44) in the case of misses (MISS) and 2.26 (SD = 0.51) in the case of correct rejections (CR). No statistical difference appeared between these different conditions, with $F(3, 42) = 2.05$, *n.s.*, and participants seemed to exhibit a high level of confidence for the four kind of responses. Finally, participants presented the same level of confidence when they reported change as when they did not, with $t(28) = 0.78$, *n.s.* but also when a change was really present in the stimulus as when no change was present, with $t(28) = 0.18$, *n.s.* These different results suggest that participants were confident in their responses, that is, that their responses truly reflected the contents of their awareness of the stimulus.

3.2.3. Behavioral measures

Concerning accuracy (see Fig. 11), we observed the same global dynamics than in the first experiment, characterized by a decrease of the distance to target over the first trials followed by a progressive stabilization. Before going further in the analysis of accuracy, it is important to assess whether differences exist as a function both of change awareness (change detected vs. change not detected) and type of response (HIT, FA, CR, MISS). In this perspective, we performed a within-subject ANOVA with two variables: awareness of the change (seen vs. not seen) and validity (*valid*, that is CR and HIT responses, vs. *invalid* trials, that is FA and MISS responses). We observed that neither Awareness nor Validity yielded significant effects. The interaction likewise failed to reach significance, with $F(1, 29) = 0.01$, *n.s.* for the awareness effect, $F(1, 29) = 1.15$, *n.s.* for the validity effect and $F(1, 29) = 2.38$, *n.s.* for the interaction. In other words, the same evolution was observed regardless of whether participants were aware of the change and regardless of whether participants' responses were valid. Thus, we decided to continue the analysis on the average value.

The results show that mean accuracy on the first trial was 3.23 cm (SD = 0.72 cm). No statistical difference was observed with the value observed in the first experiment in absence of change with $t(21) = 0.61$, *n.s.*

We then explored the dynamics of accuracy over the entire course of the experiment. In each condition, participants were in a learning phase from the first trial onwards, as the produced response configurations became progressively closer and closer to the stimulus to be learned. Starting from the 14th trial, participants were in a steady state, as their responses configuration did not get closer and closer to the target anymore. The maximum level of accuracy was achieved with a gain of 1.53 cm so that the 15 trials on which the participants still saw the target before each response were not useful in improving accuracy. At this point, the mean level of accuracy was 1.60 cm (SD = 0.45 cm). The results showed that accuracy was not significantly different across conditions, CR trials (1.61 cm, SD = 0.47 cm), MISS trials (1.62 cm, SD = 0.44 cm), HIT trials (1.63 cm, SD = 0.47 cm) and FA trials (1.56 cm, SD = 0.37 cm)), $F(3188) = 0.142$, *n.s.* However, participants' reproductions were less accurate in this second experiment than in the first experiment in the absence of change, with $t(310) = 9.86$, $p < .01$. In other words, in this second experiment like in the first, the presence of change in the stimulus led to an increase of the distance to the target in the steady state.

A similar analysis was performed on image variability (see Fig. 12). First, the results showed that the effect of Awareness, Validity and Awareness–Validity interaction were not significant with $F(1, 28) = 1.50$, *n.s.* for the awareness effect, $F(1, 28) = 0.41$, *n.s.* for the validity effect and $F(1, 28) = 0.30$ for the interaction effect. In other words, the same evolution was observed whatever the awareness of the change and regardless of whether participants' responses were valid. Here again, we decided to continue the analysis on the average value.
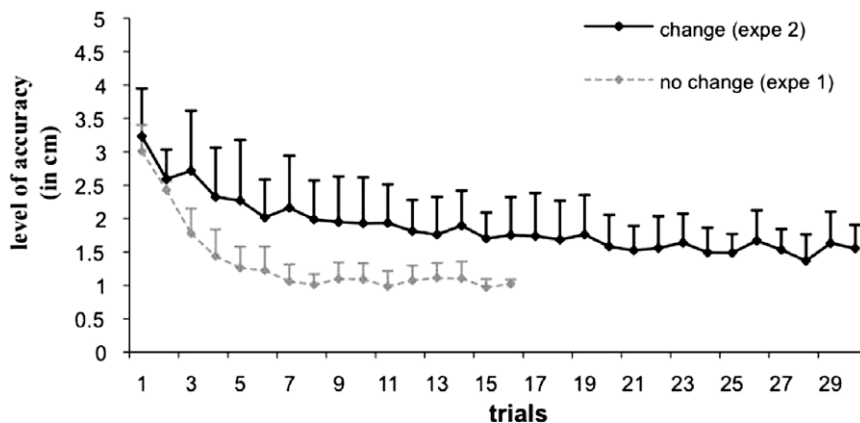

Fig. 11. Evolution of the mean value of configuration accuracy in comparison to the configuration accuracy observed in absence of change in the stimulus (Experience 1). As observed in the first experiment, change in the stimulus leads to a decrease increase of response accuracy.
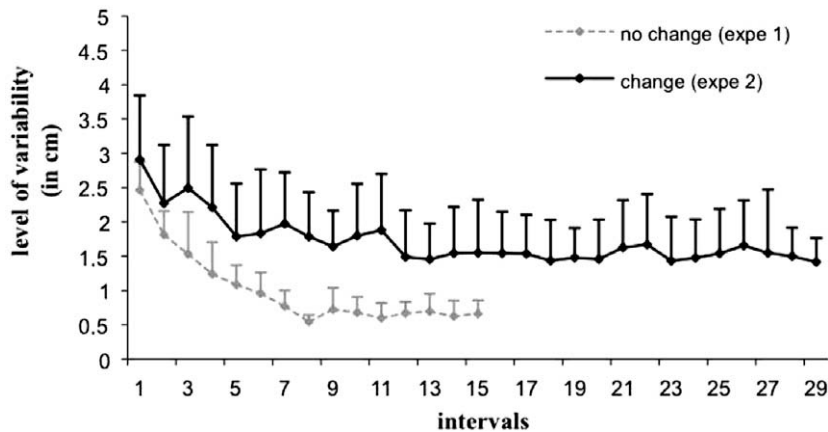
Fig. 12. Evolution of the mean value of configuration variability in comparison to the configuration accuracy observed in absence of change in the stimulus (Experience 1). As observed in the first experiment, change in the stimulus leads to an increase of response variability.

The results showed that for the first trial the mean value of variability was 2.76 cm (SD = 0.75 cm). No statistical difference was observed with the value observed in the first experiment in absence of change with $t(21) = 0.72$, *n.s.* We then explored the dynamics of the variability in the same manner as for accuracy.

The distance between responses became smaller and smaller over the first trials. Starting from the 11th interval, the results showed that the distance between responses stopped changing, suggesting that participants had reached a steady state. The maximum level of image resolution was achieved with a gain of 1.33 cm so that the 18 trials on which the participants still saw the target before each response were not useful in improving variability. At this point, the mean level of variability was 1.48 cm (SD = 0.52 cm). A one-way ANOVA showed that variability was not significantly different for CR trials (1.50 cm, SD = 0.54 cm), MISS trials (1.46 cm, SD = 0.52 cm), HIT trials (1.45 cm, SD = 0.50 cm) and FA trials (1.44 cm, SD = 0.48 cm), with $F(3229) = 0.286$, *n.s.* However, as observed in terms of accuracy, the mean variability observed in this second experiment was significantly larger than the mean variability achieved in the first experiment in the absence of change, with $t(137) = 13.40$, $p < .01$. In other words, in this second experiment, like in the first, the distance between the successive reproductions in the steady state increased in the presence of change in the stimulus.

Finally, we computed mean rotation (see Fig. 13) as in the first experiment. The results showed that the mean rotation value was 21.83° (SD = 4.44°). A *t* test performed on the rotation measure compared with random performance (rotation = 0°) showed that a positive tendency was observed in this second experiment with $t(14) = 19.82$, $p < .01$. Thus, the rotation observed in participants' reproduction was congruent with the rotation of the stimulus. We performed a within-subject ANOVA with two variables: awareness of the change (seen vs. not seen) and stimulus change (unchanging vs. changing stimulus). Interestingly, we observed that the effect of Awareness was not significant, with $F(1, 26) = 0.251$, *n.s.* In other words, behavioral adaptation was independent from awareness of the change. In particular, no difference was observed between HIT and MISS trials with $t(26) = 0.78$, *n.s.* We also failed to observe differences between rotations produced in response to changing vs. unchanging trials with $F(1, 26) = 0.419$, *n.s.* Finally, the interaction also failed to reach significance,
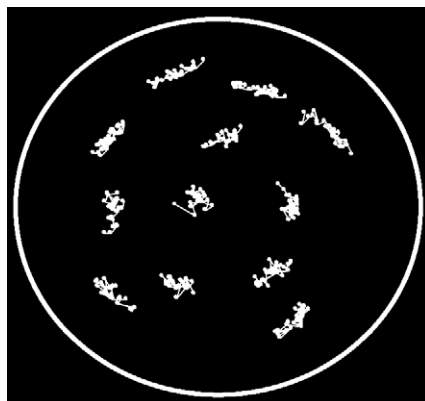

Fig. 13. Average reproduction over time characterized by a gradual rotation of the reproduced pattern.

$F(1, 26) = 3.43$, *n.s.* In the first instance, one could be surprised by this result, which suggests that behavioral adaptation was produced in the same way regardless of the presence of change in the stimulus. However, with respect to dynamical system theories, the fact that behavioral adaptation was spread out over time is directly linked to system properties. Indeed, in dynamical systems, the present state of the system is directly dependent on the state of the system in the previous trials. In this condition, a changing stimulus influences not only the state of the system at trial (n) but also the state of the system at trial $n + 1$, $n + 2$, etc. so that the effect of change is spread over time.

3.3. Discussion

The main goal of this second experiment was to improve our measures of awareness so as to provide a more precise assessment of implicit change detection. In this perspective, we modified our measures of awareness based on the observations of Cheesman and Merikle (1984) and Kunimoto et al. (2001), that is, we collected awareness reports on every trial, along with measures of subjective confidence.

This design made it possible to strengthen the results of Experiment 1. As observed in the first experiment, participants were dramatically blind to gradual changes. This "blindness" was characterized by a high level of "miss" trials and by the same proportion of false alarms and hits. This result was reinforced by the fact that the same confidence level was reported when change was present or not in the stimulus. These results suggest that no "feeling of" change was present when participants reported being unaware of the change.

Different aspects of our results thus suggest a dissociation between action and awareness in this paradigm. First, the observed increases in variability and the corresponding decreases in accuracy confirmed the presence of visual sensitivity to change in the absence of conscious experience of this change, as expressed through trial-by-trial decisions accompanied by confidence judgments. Second, the progressive rotation observed in participants' reproductions confirmed that behavioral adaptation occurred throughout the experiment. Finally, the presence of clear dissociations between participants' reports and behavioral measures reinforces the idea of a dissociation between action and awareness.

4. General discussion

The main goal of our experiments was to explore the phenomenon of "change blindness" in the context of memory-based action. Using a novel paradigm in which participants repeatedly reproduce changing displays makes it possible to explore the dynamics of implicit and explicit processes of change detection. Changes were introduced in the stimuli by rotating a dot pattern configuration progressively over successive trials. Participants' expectation of change was manipulated through instructions. By recording participants' experience of change as well as their behavioral responses to the change on a trial-by-trial basis, we assessed the extent to which change awareness and change adaptation dissociate in the presence of gradual changes.

The main results showed the following. First, conscious experience of change was influenced by the extent to which attention was directed to the presence of change through instructions. Indeed, we observed different levels of change awareness as a function of the instructions given to participants (in the presence of the same amount of change in the stimulus), with large change blindness in the "told no change" conditions and high levels of change detection in the "told change" conditions. Second, regardless of their conscious experience of the change, all participants exhibited sensitivity to the change, marked by an increase of image variability and a decrease in accuracy in the presence of change in the stimulus. Third, we observed behavioral adaptation to change in the absence of change awareness, marked by a rotation of participants' reproductions congruent with the rotation present in the stimulus. Finally, Experiment 2 strengthened our initial results by using a trial-to-trial measure of awareness coupled with subjective confidence ratings, thereby dismissing valid concerns that the measure of awareness used in Experiment 1 lacked sufficient sensitivity.

In the rest of this discussion, we focus on three central issues. First, what can we conclude about the differences between implicit and explicit change detection? Second, what is represented, if anything, when a change remains undetected? Finally, what is the role of memory representations in change blindness? We examine each issue in turn.

4.1. How does implicit detection of change differ from explicit detection of change?

Over the past ten years, researchers have increasingly focused on 'implicit change detection' (the existence of preserved information normally inaccessible to the mechanisms underlying the conscious detection of change). Stemming from different research traditions, these studies have repeatedly indicated that some aspects of change might be represented only implicitly (Thornton & Fernandez-Duque, 2002). For example, attentional blink experiments provide evidence for the existence of a representation in the absence of a verbal report of the blinked stimulus (Shapiro, Arnell, & Raymond, 1997). Likewise, inattentional blindness shows that background objects in the visual field can influence judgments even if observers are unaware of their existence (Moore & Egeth, 1997). This growing body of evidence, using indirect measures of change detection, therefore suggests that visual stimuli may be processed unconsciously.

This hypothesis is also supported by our results. Indeed, using an implicit measure of change detection, namely the variability of mnesic reproduction, we have demonstrated that even when observers cannot report a change, they nevertheless

remain sensitive to it. In the first experiment, the pattern of results obtained for the "told no change" condition shows that increases in response variability, which indicates that the change has been registered, can occur in the absence of change reportability. The same pattern of results was observed in the second experiment. This result is in line with previous findings, but our design makes it possible to go further.

First, if our results confirm the existence of preserved implicit representations without conscious awareness, they also suggest that such implicitly perceived information influences our actions. Indeed, those participants who did not report the presence of change nonetheless adapted their response to the change by producing congruent rotations of their reproductions. Such implicit behavioral adaptation has already been observed in different areas of research. For example, (Dehaene and collaborators (2001) have shown that stimuli presented too briefly to elicit awareness can nevertheless influence behavior. Along the same line, many studies have shown that motor control can be achieved independently of conscious perception of the movement, even for voluntary actions (for a discussion see Johnson & Haggard, 2005; see also Day & Brown, 2001; Desmurget et al., 1999; Goodale et al., 1986; Varraine et al., 2002). These different results are clearly congruent with our findings, in particular the fact that implicit memory mechanisms can guide our movements (Aivar, Hayhoe, Chizk, & Mruczek, 2005; Karn & Hayhoe, 2000). In addition, our results suggest that behavioral adaptation itself may be completely unconscious. Indeed, as observed by Fourneret and Jeannerod (1998), participants were neither aware of having perceived some change nor conscious of the adaptive character of their behavior.

Second, if it is clear that change sensitivity may occur in the absence of explicit change detection, the difference between noticed changes and unnoticed changes remains an open issue. Most theories of consciousness assume that when participants are consciously aware of some state of affairs, information processing is more efficient than when they are unaware (Baars, 1988; Cleeremans, 2005; Dehaene, Sergent, & Changeux, 2003; Tononi, 2004; Tononi & Edelman, 1998). If so, information processing with consciousness should result in more efficient information processing than when awareness is absent. However, recent findings suggest that this is not always the case (Lau & Passingham, 2006): observers may sometimes exhibit the same level of performance with or without consciousness (see also Cleeremans, 1997, for a related example in sequence learning). Our findings support this observation. As expected, different levels of awareness were observed as a function of the instructions, with large change blindness in the "told no change" condition and high levels of change detection in the "told change" condition. In other words, conscious experience of change was influenced by attention (see also Rensink, 2002; Simons & Levin, 1997; Simons & Mitroff, 2001; Simons & Rensink, 2005; Triesch et al., 2003). However, the level of change sensitivity was similar regardless of the presence or absence of explicit experience of change. Indeed, regardless of their verbal reports, participants exhibited the same level of change sensitivity (i.e., the same increase in response variability) and the same adaptation to this change (i.e., the same amount of response rotation). This finding suggests that information processing is no more efficient when participants are consciously aware than when they are unaware of the change (see also Laloyaux et al., 2006, 2008).

4.2. What is represented, if anything, when a change remains undetected?

Leaving aside for the time being the issue of differences between implicit and explicit processes of change detection, a second key question is the existence of implicit representations, and if so, the nature of these implicit representations. Classically, change blindness has been taken to constitute an exhaustive measure of visual short-term memory. In particular, inability to use identity information to detect changes in unattended items has been interpreted as evidence that we do not represent items that we are not currently attending (Rensink, O'Regan, & Clark, 1997). Although this conclusion may be appealing, the possibility remains that more sensitive measures than change detection provides would reveal the existence of previously undetected representations of change. Over the past ten years, researchers have focused increasingly on this second hypothesis. Different studies (see for instance Debner & Jacoby, 1994; Destrebecqz & Cleeremans, 2001; Dienes & Perner, 1999; Greenwald et al., 2003; Merikle et al., 2001) have suggested that the brain can represent and process information outside the focus of attention or below the level of awareness. If such findings have opened the door to demonstrating implicit sensitivity to change, they also suggest that explicit change detection measures are underestimating our ability to process and represent changes in our visual system. As a case in point, a recent study by Hollingworth and Henderson (2004) suggested an implicit updating of the visual memory in absence of explicit change detection and concluded that demonstrations of change blindness therefore cannot be taken as strong evidence that visual scene memory is absent (see also Simons, 2000). However, if the relationship between visual memory and explicit change detection is a crucial point in our understanding of change blindness, it is quite surprising to note that few studies have genuinely attempted to approach the nature of the mnesic representation. Our study was an attempt to do so, specifically by means of asking participants to provide detailed responses to each stimulus, which in turn made it possible to assess, on a trial-by-trial basis, the extent to which behavior would be adapted to the changing stimulus.

Clearly, our findings are congruent with the previous studies described above. Specifically, our data contribute to the growing body of evidence demonstrating that explicit change detection underestimates the contents of visual memory (Fernandez-Duque & Thornton, 2000; Hayhoe, Bensinger, & Ballard, 1998; Henderson & Hollingworth, 2003; Hollingworth & Henderson, 2002; Hollingworth, Williams, & Henderson, 2001; Williams & Simons, 2000). Indeed, using a measure that is more sensitive than verbal reports, we have shown that more information is represented in memory than verbal responses indicate (see also, Hayhoe et al., 1998; Fernandez-Duque & Thornton, 2000). These results thus strengthen the argument that the standard change detection paradigm is not well suited for investigating the detail and complexity of representations of

change in memory. Inferring what an observer represents or is aware of while viewing a scene on the basis of explicit verbal change detection alone is, at the very least, questionable.

Our findings thus challenge the hypothesis that change blindness results from the fact that observers do not retain many visual details from one view to the next (Phillips & Singer, 1974; Pollack, 1972; and Pashler, 1988), suggesting instead the existence of unconscious representations of change. However, the nature of such representations remains uncertain. Two accounts may be proposed. A first account consists in stating that participants merely form a new representation on each trial. By this account, each target configuration simply elicits a new representation in memory. This account could be appropriate to explain the results observed in the "told change" condition where subjects were explicitly looking for changes, particularly since participants reported several items as perceived during the experiment in the recognition task. However, this first account cannot explain the results obtained in our second changing condition, where participants thought they were always seeing the very same configuration. Moreover, all participants reported only one stimulus as perceived in this condition. Finally, the improvement in accuracy during the first trials for the different conditions is not congruent with this first hypothesis either. If a new representation were formed on each trial, any improvement in accuracy should be observed during the first trials. Hollingworth and Henderson (2004) have proposed a second possible explanation, namely the implicit updating hypothesis. These authors suggested that visual memory for the scene could be incrementally updated with changes in the environment, even when participants remain unaware of the occurrence of changes (Hollingworth & Henderson, 2004). In our situation, subjects could form a representation at trial one and then implicitly update that representation throughout. This alternative is congruent with the "overwriting hypothesis" (Beck & Levin, 2003; Becker, Pashler, & Anstis, 2000; Brawn, Snowden, & Wolfe, 1999; Irwin, 1992; Landman, Spekreijse, & Lamme, 2003; Levin, Simons, Angelone, & Chabris, 2002; Pashler, 1988; Phillips, 1974; Rensink, O'Regan, & Clark, 1997; Silverman & Mack, 2001; Tatler, 2001; Wolfe, 1999), that is, the fact that the representation of the pre-change information is erased or overwritten by the post-change information. Here again, our results (particularly the recognition results) are not completely congruent with this interpretation. Indeed, if the pre-change information had simply been erased or overwritten by the post-change information, participants should have chosen the pattern perceived in the final trial as the target. However, we observed no preference for the final stimulus. Further studies are clearly needed to disentangle these two alternatives.

4.3. What is the involvement of memory representations in change blindness?

Finally, our findings leave open an important question: if unconscious representations of change are as precise and detailed as our results suggest, why do they fail to make it possible for changes to be detected? In this respect, different authors have offered several accounts of change blindness (see Simons (2000) for a review). Two possible explanations have already been discussed, namely the failure to encode or represent the pre-change and/or post-change information (Noë, Pessoa, & Thompson, 2000; O'Regan and Noë, 2001, 2002), and the overwriting hypothesis. However, these two hypotheses seem unable to account for change blindness. Other possibilities have been proposed to explain change blindness. A third possibility is the "Feature combination" hypothesis. This account suggests that an integrated representation is formed based on both pre- and post-change displays. This integration would then make change detection impossible. If so, any pattern presented in the recognition task should match with the representation in memory. In other words, no pattern should be recognized as the stimulus, or at least, the confidence associated with this choice should be low. However, all participants recognized one of the patterns as the stimulus, and they did so with a high level of confidence. Some authors have also assumed that "everything is stored but nothing is compared". In other words, some representation is formed both for the pre-change and the post-change display, but no comparison is made between these two representations when change blindness occurs (Angelone, Levin, & Simons, 2003; Hollingworth & Henderson, 2002; Mitroff et al., 2004; Ryan & Cohen, 2004; Scott-Brown, Baker, & Orbach, 2000; Shore & Klein, 2000; Silverman & Mack, 2006; Simons, 2000; Simons, Chabris, Schnur, & Levin, 2002). Importantly, participants did not explicitly compare the two until prompted. This explanation is congruent with our results since change detection occurs only when subjects are explicitly looking for changes. However, this alternative does not explain the dissociation we observed between conscious experience of change and behavioral adaptation.

Finally, another possibility congruent with our findings, was proposed by Hollingworth and Henderson (Hollingworth & Henderson, 2004; see also Hollingworth, 2006a, 2006b)'s threshold model for conscious change detection. Congruently with active vision theorists (Ballard, Hayhoe, & Pelz, 1995; Findlay & Gilchrist, 2003; Gilchrist, Brown, & Findlay, 1997; O'Regan & Noë, 2001), Hollingworth (2006a, 2006b) suggests that vision is a dynamical process that involves both endogenous and exogenous noise. For example, saccades, head and body movements or eye blinks are different endogenous sources of visual changes that should be ignored when making inferences about the external world. Thus, the visual system must continuously compute which changes stem from endogenous sources (internal errors) and which stem from actual changes in the environment (external changes) (Hollingworth, 2006a, 2006b). Furthermore, our visual representations themselves are probably noisy (Verghese, 2001; Wilken & Ma, 2004), so that the cognitive system is additionally confronted with the need to distinguish between noise and signal. Thus, Hollingworth (2006a, 2006b) argued that the discrepancy between two representations has to exceed a given threshold for the difference to be interpreted as a change. Weak changes, in contrast, are taken as noise and hence simply fail to reach awareness. Such an argument echoes recent findings in the motor domain. According to Frith, Blakemore, and Wolpert (2000), for instance, one of the fundamentals functions of consciousness is to maintain the stability of our representations of the world, that is, to preserve the same conscious content in spite of continuous changes in external stimulation. As argued by Frith et al. (2000), "the changes in representation that result from

our own movements are entirely predictable on the basis of those movements and therefore do not require our attention. It seems plausible that to be aware of representations which changed every time we moved our bodies, or even our eyes, would be a positive disadvantage" (p. 1775).

Our results are generally congruent with this threshold model: The changes present in our stimulus would thus be too weak to reach awareness, yet strong enough to induce behavioral adaption (see also Cleeremans, 2005; Cleeremans & Jiménez, 2002 for similar ideas in the implicit learning literature). As Hollingworth (2006a, 2006b) noted, below the threshold, the visual system could nevertheless remain sensitive to weak change and initiate corrective behavior without awareness. Note that the threshold required for a given change to reach awareness clearly depends on top-down information in our paradigm, since information that the stimulus could be changing indeed results in more change detection than when no such information is provided to participants.

In this model thus, noisy, weak representations of change drive behavior without accruing sufficient strength to reach awareness in most cases. Such noisy mnesic representations (Giraudo & Pailhous, 1999) populate a sort of psychic twilight, as envisioned by Leroy-Gourhan (1964), who wrote that "[] most of the chains which took place from waking to bedtime call only a weak conscious intervention; they unwind not of the automatism for which the intervention of the consciousness would be useless, but in a psychic twilight of which the participant goes out only in case of unforeseen circumstances in the progress of sequences. In the gestures which we execute during the dress, during the meal, during the writing, during our movements and transports, however exceptional is the return for the lucidity, it is decisive … We cannot imagine a behavior which requires a continuous lucidity, nor a behavior without any conscious intervention; the first one would request a reinvention of every part of the smallest part of the movement, the second would correspond to a brain totally conditioned" (p. 29).

5. Conclusion

Using a novel methodological approach based on mnesic reproduction and on the analysis of response variability, we explored change blindness to action in the presence of gradual changes. Our method, through which people provide both behavioral and change detection measures on a trial-by-trial basis, makes it possible, unlike previous results (e.g., Hollingworth and Henderson (2004), to track the dynamics of sensitivity to change over the entire experiment. Our main results replicated the results of previous studies suggesting dissociations between implicit and explicit processes of change sensitivity. However, our study also extended these previous findings by documenting the nature of the dissociation and the nature of the mnesic representation. Taken together, these different results provide insights into the origins of change blindness as well as into our understanding of implicit change sensitivity.

Acknowledgments

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