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Subjective report of eye fixations during serial search

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ABSTRACT

Humans readily introspect upon their thoughts and their behavior, but how reliable are these subjective reports? In the present study, we explored the consistencies of and differences between the observer's subjective report and actual behavior within a single trial. On each trial of a serial search task, we recorded eye movements and the participants' beliefs of where their eyes moved. The comparison of reported versus real eye movements revealed that subjects successfully reported a subset of their eye movements. Limits in subjective reports stemmed from both the number and the type of eye movements. Furthermore, subjects sometimes reported eye movements they actually never made. A detailed examination of these reports suggests that they could reflect covert shifts of attention during overt serial search. Our data provide quantitative and qualitative measures of observers' subjective reports and reveal experimental effects of visual search that would otherwise be inaccessible.

1. Introduction

Humans can readily describe their own thoughts and behavior, but is this report a faithful description of the underlying cognitive process? In experimental psychology, subjective reports are often considered to be suspicious, hardly reproducible and reflective of genuine mental operations (Nisbett & Wilson, 1977). Yet accurate or not, introspection is a fundamental ability of human cognition. In everyday life, people use introspection to describe for instance the successive steps in their reasoning or to estimate their confidence in a decision. This ability also plays an important role in learning (Roebers, Schmid, & Roderer, 2009). Modern psychology is thus in need of a rigorous and systematic exploration of such metacognitive functions. The present study proposes a detailed comparison of objective and subjective data and provides an estimate of the quality of subjective reports for each trial.

While experimental psychology initially made a strong appeal to incorporate introspection as an experimental method, behaviorism raised strong doubts on this procedure's capacity to provide detailed descriptions and justifications for our own behavior. John Watson, one of the founders of behaviorism, criticized the subjectivity of introspection and stated that "we find as many [introspective] analyses as there are individual psychologists" (Watson, 1925). Doubts were further strengthened in the 1970s when experimental evidence revealed that subjects were unaware of many of the biases in their choices (Nisbett & Wilson, 1977). Recently, subjects were even found to provide justifications for a decision they never made (Johansson, Hall, Sikstrom, & Olsson, 2005). These results clearly show that introspection has limits and that observers may confabulate. Other studies revealed that intentional motor actions can affect the subjective timing of internal (Banks

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& Isham, 2009) and external events (Haggard, Clark, & Kalogeras, 2002). Subjective estimates should therefore not be considered as direct "read-outs" of subjects' mental events (Miller, Vieweg, Kruize, & McLea, 2010). The measurement methods have their own limitations and the collected empirical data need to be carefully controlled and interpreted (Bratzke, Bryce, & Seifried-Dubon, 2014; Miller et al., 2010).

However, Ericsson and Simon (1980) stressed the dependence of subjective data measurement on the methods used. They proposed a classification of introspective tasks and showed that verbal reports can be accurate when the introspected information is relevant to the present task and is immediate or present in short-term memory (Ericsson & Simon, 1980). In these conditions, verbal reports can be a remarkable reflection of objective behavior (Dulany & O'Connell, 1963). Ericsson and Simon (1980) thus provided a simple and robust theory of verbal reports, which suggested that introspection only has access to the transient cognitive representations maintained in working memory. The Global Workspace theory of consciousness (Baars, 1988, 1997; Dehaene & Changeux, 2011; Dehaene, Kerszberg, & Changeux, 1998; Dehaene, Sergent, & Changeux, 2003) made a similar postulate, stating that what we subjectively experience is information present in a central store (workspace) which broadcasts information flexibly and therefore makes it available for verbal or non-verbal report.

Although Ericsson and Simon's theory of introspection has rarely been tested explicitly, subjective reports continue to be used extensively in experimental psychology in simpler form, even if their relation to objective behavior is unclear. To name but a few examples, participants subjectively rated the visibility of a stimulus (Del Cul, Baillet, & Dehaene, 2007; Sergent, Baillet, & Dehaene, 2005; Seth, Dienes, Cleeremans, Overgaard, & Pessoa, 2008), estimated the timing of internal decision events (Libet, Gleason, Wright, & Pearl, 1983) or bet on the accuracy of their response (Persaud, McLeod, & Cowey, 2007). In these experiments, observers did not provide a complex verbal description of their mental processes. Rather, they gave a quantified estimate of a purely subjective experience. Several philosophers and experimenters argued that a thorough description of human cognition has to account for both aspects of behavior, the objective outcome measured by the experimenter and the subject's reported experience, and to understand how these two are related (Dehaene & Naccache, 2001; Dennett, 1991).

Recent studies revealed that it is possible to collect subjective reports on every trial and to compare them with objective measures. For instance, observers can be asked to quantitatively estimate the duration of their own response time which can then be contrasted with the 'real' response time (Corallo, Sackur, Dehaene, & Sigman, 2008; Marti, Sackur, Sigman, & Dehaene, 2010). Results showed that estimates of response times tightly correlated with objective ones and were sensitive to the same experimental factors (Corallo et al., 2008). However, when asked to perform two tasks in close succession, subjects were unaware of their slowing-down on the second task. These results fit squarely within Ericsson & Simon's (1980) model and the global workspace perspective by providing evidence that introspection can be accurate when it comes to tasks that successively occupy the conscious workspace, but is blind to any process occurring outside this central system. Although these results can be considered as a sign of accurate introspection, other studies revealed that estimated response times can be influenced by other sources of information, such as the perceived difficulty of the task (Bryce & Bratzke, 2014) or subjects' own motor responses (Bratzke et al., 2014). It appears that the combination of subjective and objective measures can potentially lead to novel working hypotheses and a better understanding of the architecture of human cognition. It is therefore essential to understand how humans can introspect, what the limits of this process are, and how subjective information can be distorted.

Here, we aim to test a new prediction of the global workspace model: during the performance of a long and complex task, comprising more than two serial stages, introspection should have accurate access to each of the stages successively represented in working memory, even if a whole series of goals, sub-goals, and intermediate representations unfolds on a single trial. Metacognitive information might not be necessary to perform the task itself but the conscious representation of each sub-goal should make it available for later report. In the present experiment, we explored to what extent subjects are able to retrieve this information if they are asked to. A direct comparison of objective events and subjective reports during such a chain of cognitive events would allow us to explore the consistencies of and differences between the observer's conscious experience and actual behavior within a single trial. An experimental paradigm that should allow us to objectively assess the successive sub-goals of a task is visual search. In this task, an observer looks for a target among distractors, for instance the letter T among multiple Ls. When the target is defined by a conjunction of features, visual search is a serial and effortful process that requires attentional control, which stands in sharp contrast to the automatic and parallel search that occurs when the target is defined by a unique feature (Bergen & Julesz, 1983; Shiffrin & Schneider, 1977; Treisman & Gelade, 1980; Wolfe & Horowitz, 2004; Woodman & Luck, 1999). The sequence of eye fixations follows a serial strategy predetermined by the subject's goal (Godwin, Benson, & Drieghe, 2013; Motter & Belky, 1998) – an ideal situation in which the Ericsson and Simon (1980) model predicts accurate introspection of each step.

The eye movements recorded during an overt serial search provide objective markers of the successive steps during task execution. How can we determine whether subjects are conscious of these intermediate goals? In the present experiment, we asked subjects to report the sequence of their eye movements after each trial, using a series of mouse clicks. These subjective reports thus consist in a sequence of spatial locations which can be directly compared to the sequence of eye fixations. Such data should allow us to test three different hypotheses regarding subjects' introspection. First, subjects might have absolutely no introspection regarding their motor behavior. Faced with a given display, subjects may adopt a specific strategy and simply re-enact it when asked to introspect. Second, subjects might have partial or indirect information about their own behavior. They might know how much time they spent doing the search task without having a detailed memory of their eye movements. When asked to introspect, subjects would assume they made more eye movements in trials where they were slower to respond. Third, subjects might have a detailed representation of their own eye movements, or in other words, genuine introspection.

In order to disentangle these hypotheses, unbeknownst to the participants, we presented the same visual displays twice on two distinct trials. We expected the response time and the precise trajectory of the eyes to vary between two repetitions of the same display. If subjects were re-enacting the same strategy, subjective reports should be essentially driven by the visual display and not by the objective behavior. Alternatively, if subjects were inferring their reports from the approximate duration of a trial, these reports should be influenced by the response time of a given trial but should not be related to the movements of the eyes. The subjective report should be linked to the eye movements of a given trial only if subjects have a detailed representation of their own behavior.

2. Method

2.1. Subjects

Thirteen adults aged between 19 and 31 years participated in the study. All participants gave informed consent before testing and received a compensation of €10 after their participation. All were naïve with respect to the task and had normal or corrected to normal vision. Two subjects were rejected from subsequent analyses, one because of extremely slow response times and another one because of sleep deprivation. Eleven subjects were included in the analyses (10 women, age: $M = 24$, $SD = 3$ years).

2.2. Experimental design

2.2.1. Stimuli and procedure

The main task was a visual conjunction search in which observers had to detect a red T among green Ts, green Ls and red Ls on a gray background (see Fig. 1A). A trial began with the presentation of a fixation cross (duration: 2 s). It was followed by a set of letters (4, 12 or 20 letters, one third of the trials by condition) that remained on the screen until the participant pressed a response button. Letters were 0.88° high with an eccentricity varying from 1.49° to 14.25°. Letters were displayed according to a pattern ensuring a random but homogenous repartition in the four quadrants of the screen. The target was presented in half of the trials and the subject had to report its presence or absence as quickly and accurately as possible. After the motor response, the same display reappeared, and subjects were instructed to: "click with the mouse on each spatial location you fixated while performing the search". Each click was displayed as a black dot (diameter: 0.88°), connected to the following and preceding fixations by a straight black line. Once the subjective report was completed, subjects had the possibility to submit their answer or, if unsatisfied, to erase it and restart the introspective process. An example of a trial with accurate introspection of eye fixations is presented in Fig. 1B.

In order to verify that subjects actually introspected and did not confabulate or report a generic strategy, each display was presented twice within a block (yoked trials). Examples of yoked trials are shown in Fig. 1C–F. The visual displays in Fig. 1C and D are identical to Fig. 1E and F but the behavioral outcomes are different. There was a minimum distance of 5 trials and a maximum distance of 25 ("introspection blocks", see below) or 20 ("no introspection blocks") trials between repeated stimuli.

Subjects performed 8 blocks of trials. The first two blocks were training blocks of 6 trials each. In half of the remaining blocks, subjects performed the visual search and the introspection task ("introspection blocks", 48 trials per block). Since the report of introspection is a task in itself, we were also interested in whether it could affect the way subjects performed the visual search. To answer this question, subjects also performed blocks of trials with only the visual search task. The task was identical to what was previously described except that subjects did not have to report their beliefs regarding their behavior ("no introspection blocks", 24 trials per block). The order of the experimental blocks was counterbalanced between subjects.

2.2.2. Apparatus and eye movement measurement

The task was programmed using Matlab R2010a and the Psychtoolbox 3.0.9 (Brainard, 1997). Stimuli were presented on a 19 in. CRT screen (Viewsonic Graphic Series G90fB) with a resolution of 1024 × 768 pixels and a refresh rate of 60 Hz. The subject's head was maintained 70 cm apart from the screen with a chin and forehead rest. The subject's right eye position was tracked using an Eyelink apparatus (SR eyetracker Research, Eyelink 1000, $f = 35$ mm) with a 500 Hz sampling rate. The apparatus was calibrated prior to each block. When the right eye could not be tracked, the left eye was tracked instead (1 subject). The eyetracking data was imported into Matlab using EDF Converter 3.1 (SR Research) and Eyetracker Output Utility 1.20. We used an automated algorithm (Engbert & Kliegl, 2003) to separate saccades and fixations in eye movements. Based on previous studies and inspection of raw data, we set the two parameters of the algorithm to be, the minimum duration of the saccade and the velocity threshold, at 12 ms and 6 times the mean velocity respectively.

2.3. Data preprocessing

Trials with response times exceeding three standard deviations above the mean across all trials or inferior to 200-ms were excluded from further analysis (mean across participants: $M = 1.52$, $SD = 0.72\%$ of trials with introspection task; $M = 0.84$,

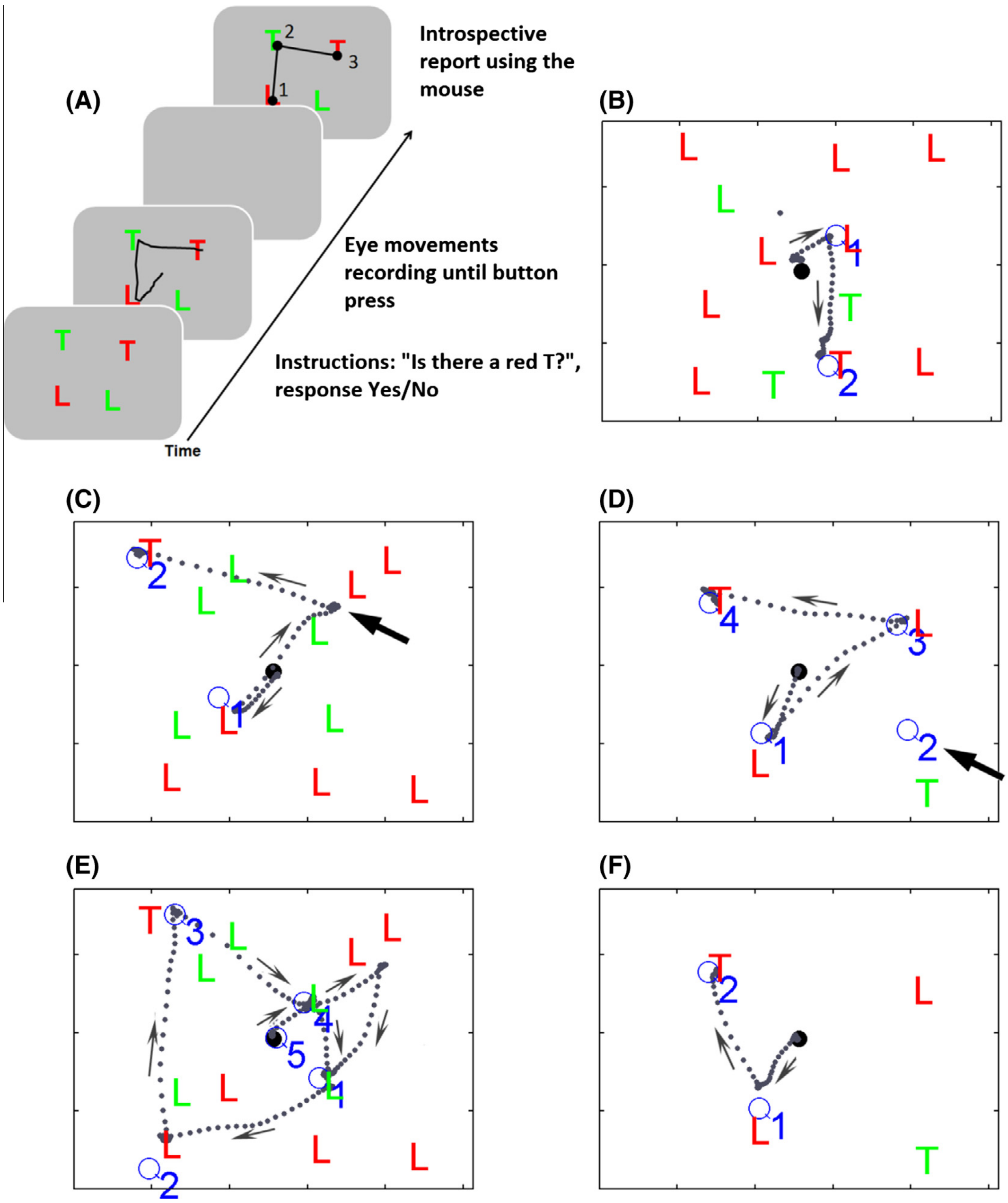

Fig. 1. (A) Schematic representation of a hypothetical trial. Participants viewed a display composed of red or green Ts and Ls on a gray background. Eye position was monitored while the participants tried to detect the presence of a red T. Once the present or absent response was made, the display vanished, then reappeared and the participants to click with the mouse on each spatial location they fixated while performing the search on that trial. (B–D) Schematic representation of real trials from one subject (the size of the stimuli was increased for display purposes). Gray dots represent eye positions and blue circles the subjective reports numbered in the reporting order. Subjects correctly introspected all of their eye fixations on some trials (B) but not on others (C–E). An eye fixation could be missed (C, arrow) or a fixation could be erroneously reported (D, arrow). (E and F) Each display was presented twice in a session (yoked trials), allowing a direct comparison of subjective and objective data for identical displays (stimuli in E and F are identical to C and D). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

SD = 0.83% of trials without introspection task). We also rejected trials in which the subject was not fixating the center of the screen at the beginning of the trial (eye position more than 3° away from the fixation cross during a 200-ms baseline period preceding stimuli onset: *M* = 14.11, *SD* = 15.92% of trials with the introspection task; *M* = 13.50, *SD* = 10.21% of trials without introspection task). Finally, in some trials, subjects did not move the eyes at all (*M* = 5.52, *SD* = 11.97% of trials with introspection task; *M* = 2.75, *SD* = 6.33% of trials without the introspection task) and/or did not give any subjective report (*M* = 7.58, *SD* = 11.04% of trials with the introspection task). Since our objective was to explore introspection of eye movements within trials, we selected trials in which both eye movements and subjective reports could be recorded.

2.4. Matching algorithm

We designed an algorithm to quantify the goodness of match between objective and subjective eye fixations. If introspection were actually related to eye fixations, the spatial distance between a fixation and its related subjective report should be smaller than the distance for any other combination of eye/reported fixation in the same trial. Therefore, for each combination of "eye fixation – reported fixation" within each trial, we computed the spatial distance between the eyes and the reported position. Repeating this operation for each possible combination resulted in a distance matrix, the dimensions of which being the locations of eye fixations and the locations of the reported fixations. Each cell of this matrix corresponded to the distance for a given pair "eye fixation – reported fixation". For each eye fixation, the closest subjective report was considered as a potential match. Note that this method allows multiple eye fixations to be matched with a single reported fixation.

The next step was to determine whether this potential match was valid. We applied an arbitrary criterion above which a trio would not be considered a valid match. To determine such criterion, we computed the distribution of the distance matrix in three situations: real trials (eye fixations and subjective reports belong to the same trial), yoked trials (eye fixations and subjective reports belong to different 'yoked' trials), and random trials (eye fixations and subjective reports belong to different trials randomly selected with the condition that they had the same set size and target presence). This revealed that some combinations in real and yoked trials had a smaller distance compared to random trials (the distribution averaged across subjects can be seen in Supplementary Fig. 1). Therefore, for each subject, we located the minimum between the two peaks of the distribution and used that value (mean across subjects: $M = 3.65$, $SD = 1.86°$) as a criterion below which the combination was considered a valid match between the subjective report and the position of the eyes.

Other methods to analyze similarities between eye movements have been previously developed. For instance, in the string edit method, the eye fixations are labeled according to a grid superimposed onto the space where the eye movements have been executed (Brandt & Stark, 1977; Cristino, Mathot, Theeuwes, & Gilchrist, 2010; Hacisalihzade, Stark, & Allen, 1992). The similarity between two scanpaths is estimated by the transformation of one string to the other (insertion, deletion, substitution of individual labels). The use of a grid is, however, problematic for our purpose. The size of areas of interest is arbitrary and can heavily influence the match between objective and subjective paths. If areas of interest are too small, a subjective report might not be associated with the corresponding eye fixation even if they are close to each other, simply because the two were assigned to different areas. On the other hand, subjective reports and eye fixations might be incorrectly matched if the areas of interest are too large. Other methods such as the FuncSim (Foerster, Carbone, Koesling, & Schneider, 2011, 2012; Foerster & Schneider, 2013) or MultiMatch algorithms (Dewhurst et al., 2012) compare numerous properties of eye movements in order to estimate their (dis)similarity. However, here we are not comparing two sequences of eye movements. Instead, scanpaths are compared to mouse clicks and it is unclear how these algorithms could be adapted to such data. Even if it could be done, our aim was not only to estimate the similarity between objective and subjective data but also to determine which eye fixations were presumably reported correctly. Therefore, we opted for a simpler approach, based on a nearest neighbor, which could be easily adapted for the purpose of the present experiment and perfectly fulfilled our needs. The algorithm we used is specifically designed for the experimental paradigm: participants were asked to report their eye fixations. Thus, our method estimates within each trial which eye fixations can be considered as reported by the subject. In addition, while more sophisticated algorithms were tried and may lead to an even better percentage of matches, this one was robust and did not require any subjective adjustments.

3. Results

3.1. Objective behavior

The overall performance in the serial search task was high ($M = 95.07\%$, $SD = 7.90\%$ correct responses). Analysis of response times (repeated-measure ANOVA) revealed typical effects of serial search (Fig. 2A). We found a significant main effect of set-size ($F(2,20) = 63.08$; $p < .001$), a main effect of target presence ($F(1,10) = 34.72$; $p < .001$), and an interaction between the two ($F(2,20) = 5.66$; $p = .01$). These findings reflected a classical linear increase in response time (RT) as a function of the number of items on screen, with a steeper slope for target absent than for target present trials, indicating serial search. Similar effects were observed on the number of eye fixations (Fig. 2B, set-size: $F(2,20) = 57.96$; $p < .001$; target presence: $F(1,10) = 52.02$; $p < .001$; set-size × target: $F(2,20) = 8.94$; $p < .01$). Eye fixations were directed primarily toward distractors of the target color ($Mdn = 74.07\%$, $SEM = 4.12\%$, $Z = 1$, $p < .01$), and the number of red distractors predicted response times (Pearson's correlation performed within each subject: $Mdn = 0.37$, $SEM = 0.06$), suggesting that observers opted for a strategy focused on red items in the display.

3.2. Subjective reports

An ANOVA on the total number of subjectively reported fixations revealed similar effects as the ones observed for response times and eye fixations (see Fig. 2B). Subjects reported more fixations for larger set-sizes ($F(2,20) = 42.07$; $p < .001$) and for trials when the target was absent than when it was present ($F(1,10) = 41.02$; $p < .001$). As for the objective

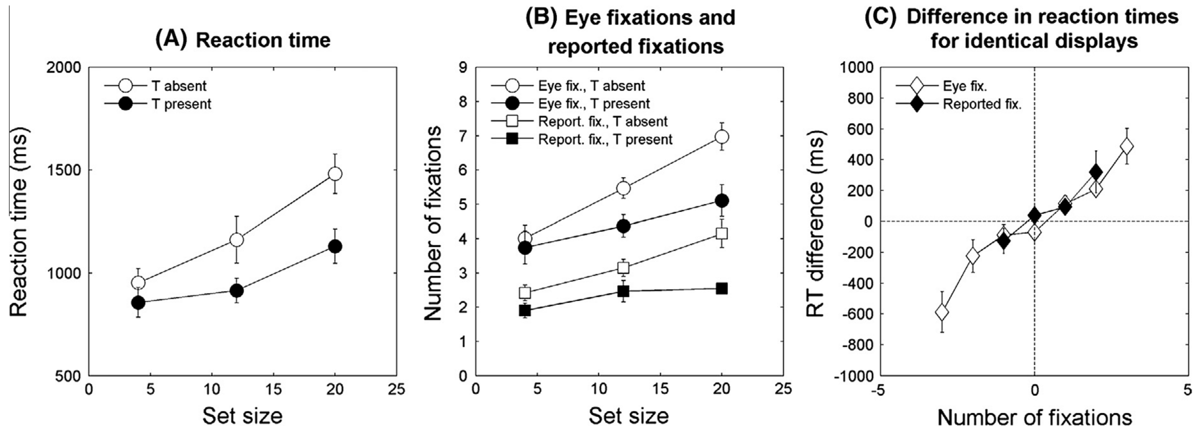

Fig. 2. Experimental effects on objective and subjective measures. Group average response times (A), eye fixations and reported fixations (B) as a function of set size and target presence. (C) Average difference in response times between two repetitions of the same display (RT for the first presentation minus RT for the second presentation of the same display), as a function of the difference in the number of eye fixations or of reported fixations.

data, the two factors showed a significant interaction (set-size × target: $F(2,20) = 5.65$; $p = .01$). Furthermore, most reported fixations landed on red items (*Mdn* = 80.63%, *SEM* = 3.5%, $Z = 0$; $p < .001$).

In our paradigm each trial was presented twice to the subject (see Section 2 and Fig. 1C–F). Within a pair, we expected an increased number of real eye fixations for the trial with a slower RT. We computed the difference in RT between the first and the second presentation, and compared them to the equivalent difference in the number of real fixations. RT differences were larger for trials with a large difference in numbers of eye fixations ($F(6,60) = 14.81$; $p < .001$, Fig. 2C). Note that the differences could be negative or positive (subjects were not systematically faster or more efficient on later trials). Importantly, we found a similar effect in subjective reports: the number of reported fixations increased for slower RT ($F(3,30) = 4.41$; $p = .01$, Fig. 2C).

Thus, for identical displays, subjects reported more fixations for trials with slower RT. Although intriguing, this result does not necessarily reflect a genuine introspection. Subjects might be aware of the time they spent performing the visual search and adopted the strategy to report a larger number of randomly chosen locations when they were slow during the objective task (see Section 1). Consequently, we asked whether the number of reported fixations would still be related to the number of real fixations even if RTs were identical. A regression analysis revealed that in fact the number of reported fixations predicted the number of real fixations even when controlling for the difference in RT (median regression coefficient: *Mdn* = 0.34, *SEM* = 0.06, $Z = 0$, $p < .001$). This result argues against the hypothesis that subjects have only access to the time they spent on the visual search task and suggests that reported fixations were actually linked to the subject's own eye movements. Overall, these results show that subjective reports were influenced by the same experimental factors as the objective data, and single-trial measures captured variance in objective behavior.

3.3. Influence of the subjective task on the objective behavior

In our experiment, subjects had to both perform the visual search and monitor their own behavior for each trial. It is important to determine whether the subjective task could have altered the main objective task in a way that would make any comparison impossible. It would be possible for instance that the effort needed to memorize the successive eye movements in order to later report them would slow down the visual search. To probe this, all subjects participated in visual search with or without the added requirement of reporting their eye movements. A factor Introspection, reflecting blocks with or without subjective reports, was introduced in the ANOVAs. We tested the assumption of sphericity with Mauchly's test and a Greenhouse–Geisser correction was applied if appropriate. On average, subjects were slower to perform the visual search when they also had to monitor their eye movements (Fig. 3A, $F(1,10) = 7.02$; $p = .02$, average difference in reaction time: 145 ms). The onset time of the first fixation tended to be later in blocks with introspection (Fig. 3B, $F(1,10) = 4.22$; $p = .07$), but the effect of introspection reached significance only for the onset time of the last eye fixation (Fig. 3C, $F(1,10) = 7.18$; $p = .02$). The duration of each fixation did not increase when observers had to introspect (Fig. 3D, $F(1,10) = 1.09$; $p = .3$). Most crucially, no interaction with the other factors included in the ANOVA was found (all *ps* > 0.2). Thus, participants were slightly slower to start and to finish the visual search when they also had to report their eye positions but there was no additional processing time during the search itself.

Another important point is whether the subjective task modified the observer's spatial pattern of eye movements. We compared numerous physical properties of eye movements in blocks with versus without introspection. Introspection affected neither the number of eye fixations (Fig. 3E, $F(1,10) = 1.83$; $p = .2$) nor the saccade length between fixations (Fig. 3F, $F(1,10) = 0.14$; $p = .72$). The distances between fixations and distractors were slightly larger (Fig. 3G,

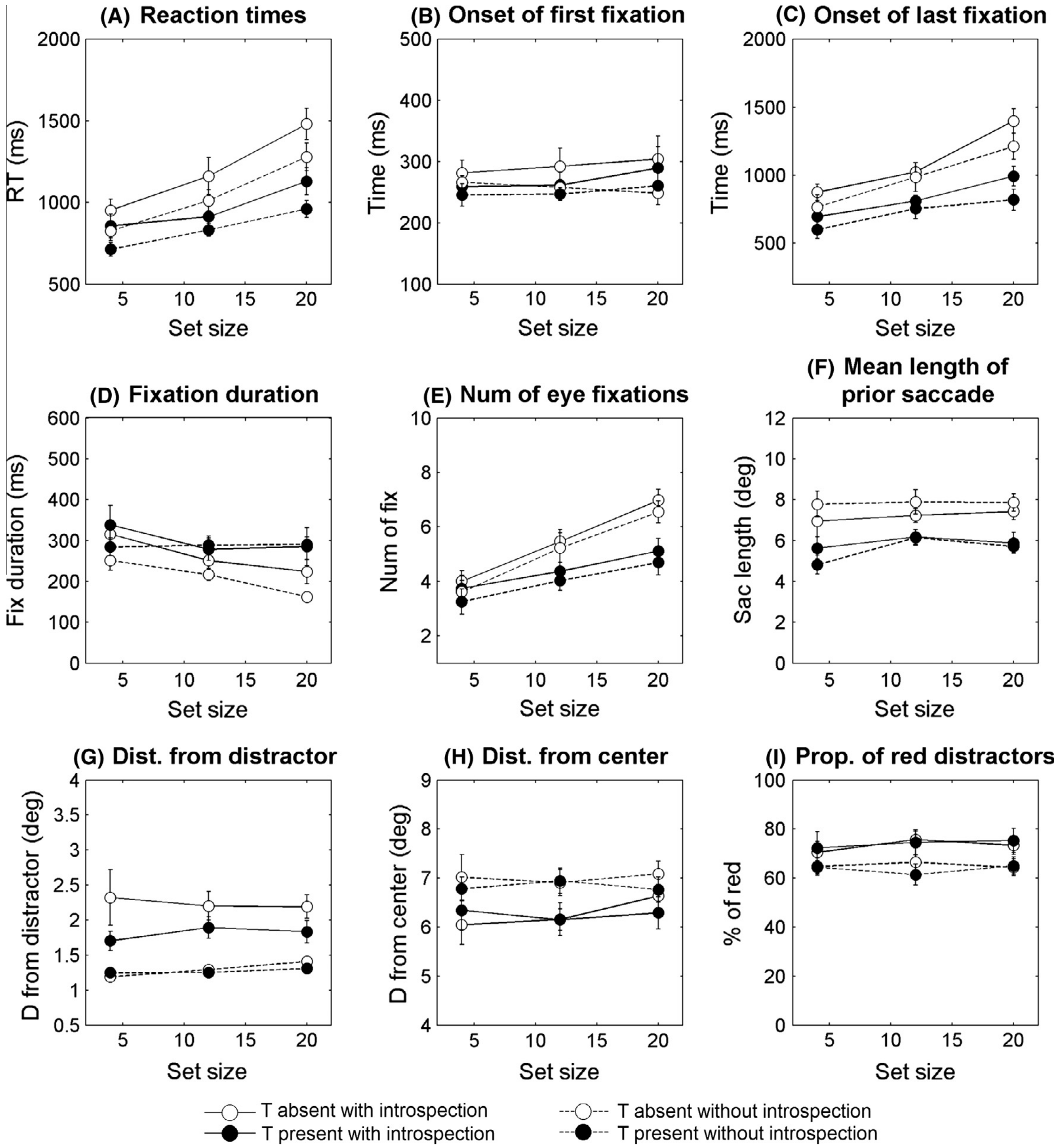

Fig. 3. Effects of introspection on serial search. Panels A–I present physical properties (mean ± s.e.m.) of eye movements in blocks with or without introspection as a function of the number of distractors. Black dots represent target present trials, open dots target absent trials, solid lines blocks with introspection and dotted lines blocks without introspection. (A) Response times. (B) Onset time of the first eye fixation. (C) Onset time of the last eye fixation. (D) Duration of fixation. (E) Number of eye fixations. (F) Length of saccade prior to fixation. (G) Distance to the distractor. (H) Distance to the center of the screen. (I) Proportion of red distractors.

$F(1,10) = 27.62$; $p = .001$) and the eccentricity of the saccade endpoints smaller in blocks with introspection (Fig. 3H, $F(1,10) = 9.04$; $p = .01$). Finally, subjects fixated more often on items of the target's color when they had to introspect (Fig. 3I, $F(1,10) = 5.66$; $p = .04$). Again, we did not find any significant interaction between introspection and any other factors (all *ps* > 0.2). Introspection thus seemed to have only a marginal effect on the characteristics of eye movements. The effects of set-size and target presence were not significantly altered by the introspection task and were typical of serial search. As the number of distractors increased, subjects were slower to respond, made more eye fixations and each of these fixations had shorter durations.

These results show that subjective reports can provide valuable data related to the objective behavior without profoundly modifying it. Our next objective was to directly match objective and subjective reports in order to determine what kind of information subjects can consciously access.

3.4. Matching objective and subjective behaviors

We first compared physical characteristics of reported and real eye fixations. Both landed in the neighborhood of visual items but eye fixations were more distant from them than reported fixations (respectively *Mdn* = 2.45°, *SEM* = 0.17° and *Mdn* = 1.30°, *SEM* = 0.11°, *Z* = 0; $p < .001$). Eye fixations also remained closer to the center of the screen than reported fixations (*Mdn* = 6.37°, *SEM* = 0.24° and *Mdn* = 8.02°, *SEM* = 0.24°, *Z* = 1, $p < .01$). This suggests that subjects did not need to bring their eyes all the way to the item and partially relied on peripheral vision. Subjective reports instead seemed more closely related to the item targeted by eye movements.

3.4.1. Correctly reported eye fixations

The average number of eye fixations per trial was systematically superior to the number of reported fixations (Fig. 2B; *Z* = 1, $p < .01$), which shows that introspection was not perfect. Subjects did not report all eye fixations during the task, but rather a subset of them. We designed a matching algorithm to determine which reported fixation corresponded to a particular eye fixation (see Section 2). Note that this algorithm was not constrained by temporal order, and could thus find matches even if introspection was temporally scrambled relative to actual behavior. After running the algorithm, each eye fixation and reported fixation was assigned to one of three categories: correctly reported fixations, genuine eye fixations without correspondence in the subject's report (hereafter called "missed fixations"), and reported fixations unmatched with any eye fixation (hereafter called "false reports"). Illustrations of these categories can be seen in Fig. 1B–D respectively. As controls for these 'real trials', we matched the subjective reports either to the eye fixations of their corresponding yoked trial with the same target display ('yoked trials'), or to a randomly selected trial with the same set size and target presence ('random trials').

On average, half of the eye fixations could be matched to subjective reports (*Mdn* = 55.48%, *SEM* = 5.63% for real trials, compared to *Mdn* = 21.89%, *SEM* = 5.67% for random trials, *Z* = 1, $p < .01$), the other half being categorized as missed fixations (Fig. 4A). This proportion was similar for real and yoked trials (*Mdn* = 53.46%, *SEM* = 6.13%), presumably due to the similarity of eye movements in trials with identical displays and to the algorithm's capacity for matching regardless of temporal sequence. To further explore the differences between real and yoked trials, we selected trials in which three to seven eye fixations were correctly reported (on average *M* = 36.17%, *SD* = 17.29% of the total number of trials; 10 of 11 subjects had trials with at least 8 correctly reported fixations) and examined whether subjects were aware of the sequence of their eye movements. For each trial, we computed the rank correlation between the sequence of subjective reports and the sequence of eye fixations and found this correlation to be stronger in real trials (rho value: *Mdn* = 0.63, *SEM* = 0.13) compared to yoked trials (*Mdn* = 0.11, *SEM* = 0.11, *Z* = 5, $p < .01$). Fig. 4B shows for each successive eye fixations (from the first to the seventh) the average position of the related subjective report. As can be seen, the position of subjective reports increased with the position of eye fixations. Furthermore, this effect vanished when the order of subjective reports were shuffled within a trial (mean slope of a linear regression with eye fixation positions: *M* = 0.19, *SEM* = 0.08 for real trials and *M* = −0.001, *SEM* = 0.001 for shuffled sequences, $t(9) = 2.51$, $p = .03$). The same analysis in yoked trials revealed that the slope

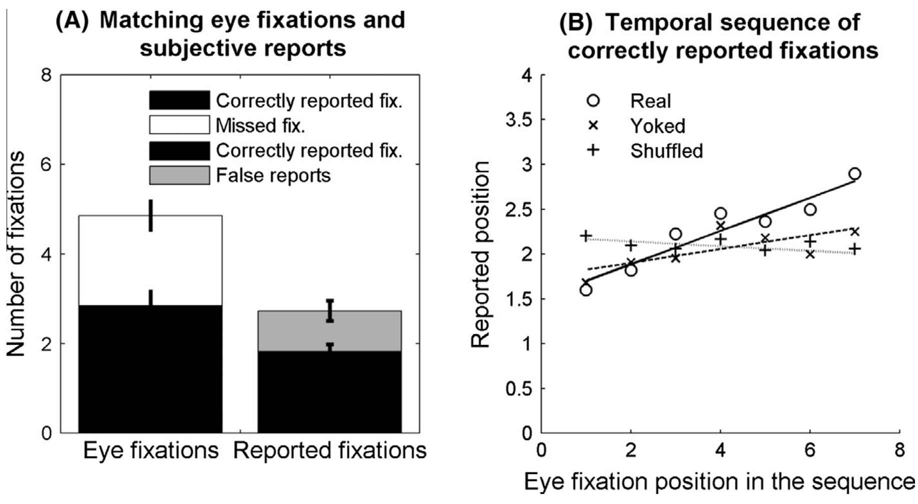

Fig. 4. Matching objective and subjective measures. Panel A presents the average number of eye fixations (left bar) and the proportions of these fixations that could be matched to subjective reports ("correctly reported fixations", black) or not ("missed fixations", white). The right bar represents the average number of subjective reports and the proportions of these reports that could be matched to eye fixations ("correctly reported fixations", black) or not ("false reports", gray). For correctly reported fixations, we asked whether the temporal order of subjective reports reflected the temporal order of eye fixations. Panel B represents the position of matched subjective reports as a function of the position of matched eye fixations (opened circles). As controls, the same analysis was conducted in yoked trials (× symbols), and after shuffling the order of subjective reports (cross symbols). Solid, dashed and dotted lines represent linear regression lines.

was positive but not significantly different from the shuffled condition ($M = 0.08$, $SEM = 0.06$, $t(9) = 1.40$, $p = .19$). Thus, spatial locations of both objective and subjective reports were similar in yoked and real trials, but the temporal sequence of reports was more consistent in real trials. Even if subjects reported only a subset of their eye fixations, the reported sequence was correlated with the actual sequence of eye fixations. These results support the hypothesis that subjects can to some extent monitor their own behavior and remember this information for later use. Having explored the partial match between objective and subjective measures, we now turn to divergences between the two.

3.4.2. Missed eye fixations

Fig. 1C shows an example of a trial with a missed eye fixation: eye fixations 1 and 3 clearly correspond to introspective fixations 1 and 2, but the second eye fixation (designated by the arrow) was not reported by the subject. As previously mentioned half of the eye fixations could be matched to a reported fixation, the other half being categorized as missed (Fig. 4A). We first tested whether missed fixations could result from limits in subjects' working memory capacities. Subjects made more than 3 or 4 eye fixations in a large number of trials, thus it is possible that missed fixations correspond to the inability of the subject to remember the entire sequence of eye movements. We computed the proportion of missed fixations as a function of the number of eye fixations in a trial (Fig. 5A). Given the variable number of trials with less than three fixations, or more than seven fixations, we grouped trials with one to three fixations and seven or more fixations. We found a significant increase in the proportion of missed fixations with increasing number of eye fixations ($F(4,40) = 6.11$; $p < .01$, $\varepsilon = 0.80$). This proportion was 42% for trials with 1–3 fixations and went up to 55% for trials with 7 or more fixations. We also examined whether some eye fixations in a sequence were more likely to be missed. For each subject, we computed the proportions of missed fixations in trials with 3–7 eye fixations. As can be seen in Fig. 5B, only the very first fixation of a sequence tended to be more often missed, irrespectively of the length of that sequence. However, this effect was weak and barely reached significance in trials with 6 eye fixations ($F(5,50) = 2.84$, $p = .05$). These results show that subjects were able to memorize the sequence of their eye movements to a certain extent but were limited in the maximum number of fixations they could remember.

The fact that missed fixations were observed in trials even with only one eye fixation suggests that a limit in working memory was not the only reason why some fixations were not reported. We measured a large number of properties of missed fixations in order to better characterize them (Fig. 5C). First, missed fixations fell less frequently on red items, suggesting that they deviated from the subjects' reported strategy (Fig. 5D, missed fixations: $Z = 23$, $p > .4$; correctly reported: $Z = 0$, $p < .001$). Second, they were on average farther away from the closest distractor (Fig. 5E, $Z = 2$, $p < .01$) and seemed to be closer to the center of the screen although this effect was not significant (Fig. 5F, $Z = 19$, $p = .24$). Third, the spatial distance traveled from the prior location tended to be larger for missed compared to reported fixations (Fig. 5G, $Z = 12$, $p = .06$). Finally, for a given saccade leading to a fixation, we computed the angle between that saccade and the previous one. The angular change in direction was more abrupt in missed compared to reported fixations both before (α *prior*, Fig. 5H, $Z = 5$, $p = .02$) and after (α *after*, Fig. 5I, $Z = 3$, $p = .01$) the fixation. These results show that eye fixations that are less likely to be reported by the observer have distinct characteristics. More generally, it seems that subjects are able to monitor their behavior to a certain extent but there are limits to this ability. These limits stem from limited memory capacities and perhaps (undetected) interruption of the ongoing motor plan by other factors.

3.4.3. False subjective reports

Some subjectively reported fixations could not be matched to any eye fixation and were thus categorized as "false reports" (Fig. 4A, $Mdn = 30.66\%$, $SEM = 6.52\%$, see also Fig. 1D for an illustration of false reports). Are they simply confabulations, or do they reflect an underlying psychological reality? To address this issue, we compared their characteristics to those of matched fixations. First, both were directed preferentially toward distractors of the target color (Fig. 6A, false reports: $Z = 5$, $p = .01$; correctly reported fixations: $Z = 0$, $p < .001$), although this effect was weaker for false reports ($Z = 8$, $p = .02$). Second, the distance to the nearest distractor (excluding the target) was slightly larger for false reports ($Mdn = 1.71°$, $SEM = 0.17°$) compared to correctly reported fixations ($Mdn = 1.14°$, $SEM = 0.09°$; $Z = 6$, $p = .01$). Thus, false reports were not randomly placed within the display. Instead, they seemed to be consistent with the observer's search strategy.

We next tested two alternative interpretations of this result. First, false reports could be unrelated to the objective behavior itself but rather could reflect an attempt of subjects to complement their subjective report. In other words, subjective reports would be a mixture of eye fixations correctly reported (genuine introspection) and false reports reflecting the observer's strategy based on the visual display (erroneous introspection). An alternative interpretation would be that false reports reflected a process that occurred during the visual search, e.g. covert attentional movements. Under this hypothesis, observers would sometimes explore the display in the typical serial manner, but using solely their attention while keeping their eyes fixed – and they would report their attention rather than their eye movements. This hypothesis would predict that such covert attentional movement should take time and thus it should impact the subject's response time. By contrast, if false reports corresponded to only erroneous reports linked to a general strategy, they should not be predictive of response times. To test this hypothesis, we computed a stepwise linear regression for each subject with the response time as the dependent variable and the number of correctly reported fixations and the number of false reports as regressors. Over the group, both regression coefficients were significantly different from zero (Fig. 6B, correctly reported fixations: $Z = 0$, $p < .001$; false reports: $Z = 4$, $p = .007$; respectively 203.67 and 136.70 ms per additional item). Thus, when subjects reported fixations that they never made, they were also slower to complete the serial search task.

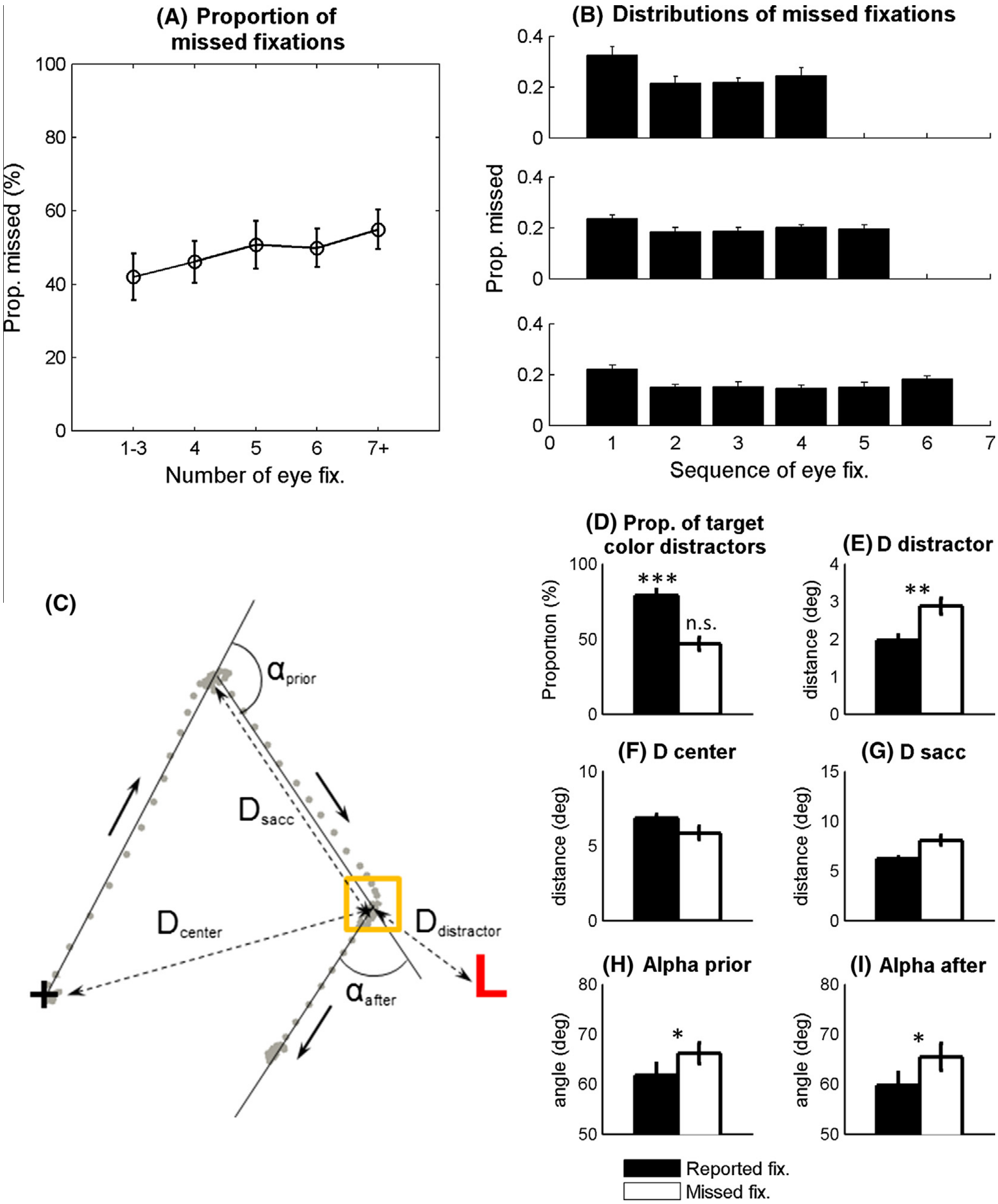

Fig. 5. Different physical properties for reported versus missed eye fixations. (A) Proportion of missed fixations as a function of the number of eye fixations. (B) Distribution of missed fixations for trials with 4, 5 or 6 eye fixations (top, middle, bottom respectively). The *x* axis represents the sequence of eye fixations and the y axis the proportion of missed fixations. (C) Schematic representation of eye movements (gray dots) during a trial. The center of the screen is represented by a cross. Starting at the large fixation cross placed at screen center, the observer explores the display through a series of eye movements (dots) consisting in an alternation of fast saccades and fixations. One of them is highlighted by the orange square. The display illustrates the various geometrical parameters that were calculated before and after this fixation (median ± s.e.m.). (D) Reported eye fixations were directed mainly to items of the target color while missed fixations were not directed to items of a particular color (median ± s.e.m.). (E and F) Compared to reported fixations, missed fixations fell further away from the distractor ($D_{distractor}$) and closer to screen center (D_{center}). (G) The saccade length prior to fixation (D_{sacc}) was slightly smaller for reported than for missed fixations. (H and I) The change in direction was similar before (α_{prior}) and after (α_{after}) missed fixations compared to reported fixations. Stars represent results of Wilcoxon signed rank tests, $^{***}p < .001$; $^{**}p < .01$, $^{*}p < .05$.

Still, it is possible that false reports reflect erroneous subjective reports. Subjects might report additional fixations because they estimated being slower on a particular trial. To test whether false reports reflected covert attention or erroneous subjective reports, we measured the durations of eye fixations immediately preceding or following false reports and compared it to the same measure for reported fixations. If subjects were actually covertly shifting their attention during

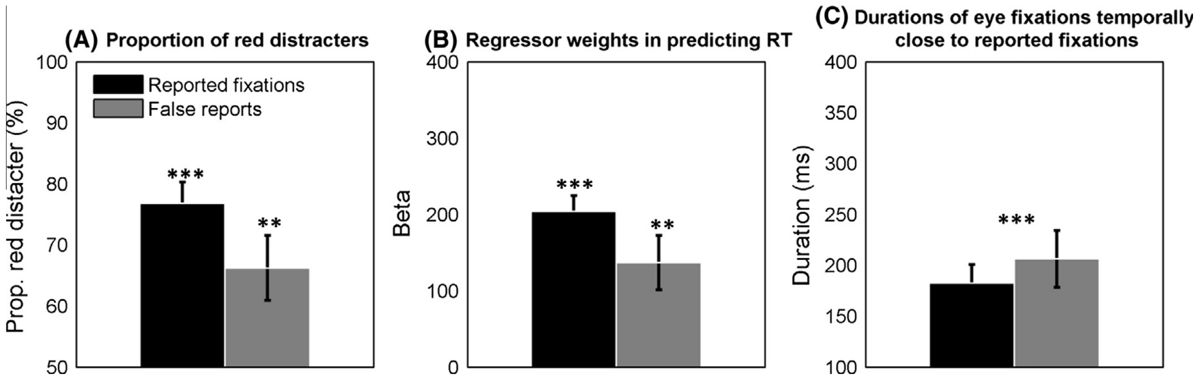

Fig. 6. Reported fixations without a match in actual eye behavior may reflect covert shifts of attention. Both correctly reported fixations and false reports were preferentially directed toward items of the target color (A). For each subject, we performed a stepwise regression with the number of introspected eye fixations and the number of false reports as regressors. Panel B shows that both regressors significantly contributed to the variance of response times (median ± s.e.m.). Panel C shows that durations of eye fixations temporally close to an false report were longer compared to the ones close to correctly reported fixations (median ± s.e.m.). Stars represent results of Wilcoxon signed rank tests, $^{***}p < .001$; $^{**}p < .01$, $^{*}p < .05$.

the visual search, their eyes should stay fixed for a longer duration, reflecting the duration of the additional attention-demanding operation. Such longer eye fixations might precede or follow the false report since the temporal order of subjective reports did not systematically match the order of eye fixations. In agreement with our prediction, from the sequence of eye fixations correctly reported by the subject, the ones in the temporal vicinity of false reports (i.e. just before or just after) lasted significantly longer than the ones for correctly reported fixations (206 ms versus 182 ms; Fig. 6C, $Z = 0$, $p < .001$). This supports the hypothesis that a covert mental operation did occur on some trials, in agreement with the subject's introspection. Note that this observation also allows us to reject the hypothesis that false reports are simply failures of our matching algorithm (if, for instance, they corresponded to an actual eye movement that was carelessly reported by an imprecise mouse click and, as a consequence, did not fall close enough to be matched by our algorithm). Under this hypothesis, there would be no reason for the added fixation time.

In summary, our results suggest that subjects' introspection is only partially accurate within a single trial. Interestingly though, false reports might not represent erroneous introspection or errors of the matching algorithm. Instead, we suggest that part of these reports reflected covert shifts of attention during serial search.

4. Discussion

The present experiment provides quantitative and qualitative estimates of observers' introspection during a visual search task. Within single trials, we confronted observers' subjective reports to the complex spatio-temporal trajectories of their eyes. We found evidence that subjects were able to provide partial but detailed information about their own cognitive operations. Subjective reports corresponded only to a subset of the real saccade endpoints, but this limited introspection was nevertheless closely related, spatially and temporally, to the objective behavior. We also identified limits of the subjects' ability to introspect. Trials with large numbers of eye movements were related to poorer introspection. In addition, eye movements unreported by the subject were different from reported eye movements and did not follow the subject's strategy for a guided search. Finally, subjective reports might potentially reveal effects of visual search inaccessible to standard objective measures. Part of the reported movements did not correspond to any actual eye movements, and yet as we shall discuss below, such reports could possibly reflect covert shifts of attention during overt serial search.

Our study was meant as a test of Ericsson and Simon's (1980) proposal that introspection should be accurate whenever the task probes the recent contents of working memory. Accordingly, subjects were placed in an effortful serial task and were asked to report their spatial eye trajectory immediately after each trial, ensuring that the relevant information was most likely to be still present in working memory and did not have to be recoded (e.g. verbalized) before being reported. We tested three hypotheses regarding subjects' ability to introspect. The first hypothesis was that observers do not have conscious access to their own behavior. Instead, subjective reports would merely reflect a re-enactment of the observer's strategy of a guided search. The analysis of yoked trials allowed us to reject this hypothesis. Even for identical displays, subjects' response times were slower when they subjectively reported a larger number of fixations. Similarly, subjects might have performed the visual search task a second time when they were asked to introspect. This second execution of the task would happen to be similar to the first one only because the conditions of execution (e.g. attention, alertness) were similar. Under this hypothesis, false reports should correspond to small variations between two executions of the same task. However, we found that false reports actually explained part of the variance of the objective behavior. Subjects were slower to perform the visual search task when they subjectively reported making more eye fixations, even if these reports could not be matched to any actual eye fixation. Thus, these results suggest that there is a link between eye fixations performed during a trial and the related subjective reports.

A second hypothesis was that participants might be able to retrieve indirect information, e.g. how much time they spent on a given trial. From this information, they would infer that trials in which they spent more time looking for the target required more eye movements but the details of these movements would remain out of reach. Contrary to this hypothesis, we found that for each trial, part of the subjective report matched the sequence of eye fixations spatially and temporally even though only a subset of eye fixations was reported. This converges with previous evidence that subjects can discriminate their own eye fixations patterns even though their performance is poor (Foulsham & Kingstone, 2013). Thus, the present results support the hypothesis that subjects do have the ability to consciously monitor their own behavior and hold part of this information, i.e. the spatial locations and the order of some of their eye fixations, in working memory until report. Note that this implies neither that subjects actually perform such introspection in everyday life nor that introspection is necessary to complete the visual search. Rather, it suggests that such metacognitive information is available and can be retrieved or memorized by subjects if needed, therefore allowing them to monitor their own behavior.

The present results converge with recent evidence suggesting that subjects are able to partially retrieve accurate information about their own cognitive processes during a visual search task (Reyes & Sackur, 2014). However, introspection is not always accurate. Indeed, there is evidence that introspection can be based on several distinct sources of information. For instance, the timing of events as perceived by subjects can be influenced by the motor responses (Bratzke et al., 2014) or by the difficulty of the task (Bryce & Bratzke, 2014). Our study is rather exploratory and we tested only two alternative hypotheses that could explain the observed results. Further investigations are required in order to determine whether subjective reports of eye fixations can be distorted by experimental manipulations or by external factors (e.g. the salience of a distractor).

An important point is whether the subjective task (which may be considered a secondary task) interferes with the execution of the primary objective task. In our study, the large memory load produced by the need to remember the successive eye movements might have affected subjects' performance in such a way that would make it incomparable to a condition without introspection. The comparison of the conditions with and without subjective reports revealed that subjects started and finished the visual search later when they also had to report their introspection. Aside from this constant addition to response times, we found no evidence of an additional process that might interact with the visual search. Furthermore, the spatial patterns of eye movements were similar in both conditions, except that eccentricity was slightly larger in introspection blocks. Thus, although the search task was delayed, once the search was started, subjects' objective behavior was similar whether or not they had to perform the subjective task. This finding is consistent with our previous research (Marti et al., 2010) and fits with the hypothesis that introspection did not require an additional process during serial search but instead a post-hoc inspection of the contents of working memory and/or immediate episodic memory.

So far, we have shown that subjective reports partially reflected subjects' objective behavior without corrupting it. How, then, are we to interpret the discrepancies between actual eye movements and subjective reports? The fact that reported fixations were spatially closer to the visual items than the corresponding eye fixations suggests a hypothesis: subjects accurately reported the successive goals of their attentional movements, but the subsequent implementation of these goals into actual eye movement could still depart from this plan in order to minimize the gaze path. Indeed, we observed that eye movements were shorter and stayed significantly closer to the center of the screen than reported movements. Both hypometricity and center bias could reflect an unconscious motor control that minimized eye path and maximized the use of peripheral vision, but occurred after the conscious planning stage and therefore could not be accurately introspected (Coeffe & O'Regan, 1987; Findlay, 1982; Zelinsky, 1996).

In addition to these inaccuracies in reporting gaze position, some eye fixations remained entirely unnoticed by the observer. There are several hypotheses which might explain this result. First, if subjects based their subjective reports on the general strategy they used during the task rather than their behavior, the fixations that were missed could correspond to those which deviate from this strategy. However, as we previously discussed, we provide evidence that subjects did not report a general strategy but were instead able to report their eye movements. Second, introspection might be limited in capacity and the number of eye fixations might have simply overwhelmed subjects' introspective ability or their working memory span, so that some steps would be lost in the subjective report. This interpretation is supported by the fact that the proportion of missed fixations increased with the number of fixations. However, we also found that the physical properties of reported and unreported eye fixations were different: missed fixations did not follow the subject's strategy, were farther away from the explored letter and closer to the center of the screen, and their saccades were longer than the saccades that could be reported. Thus, a third hypothesis is that the physical properties of these fixations could have made them more likely to be forgotten (i.e. they reached consciousness but then faded out). Distinguishing between missed and forgotten items can be extremely hard or even impossible with a posteriori behavioral methods (Block, 2005) (see Dennett, 1991 for a related distinction of 'Orwellian' versus 'Stalinesque' processes). Finally, it could be that these saccades were missed because they resulted from eye control systems inaccessible to consciousness. There is prior evidence that the eye movements triggered by the automatic capture mechanism, unlike the strategic ones, can remain unconscious (Mokler & Fischer, 1999; Nieuwenhuis, Ridderinkhof, Blow, Band, & Kok, 2001; Posner & Rothbart, 1998; Theeuwes, Kramer, Hahn, & Irwin, 1998). Thus, we suggest that missed eye fixations could be a mixture of eye movements that failed to be consolidated into memory and eye movements that could not be reported because they were programmed at an automatic, unconscious level.

Conversely, subjects also reported fixations at locations that could not be matched to any actual eye fixation. This could simply reflect errors in the subjective reports. In the present experiment, subjects might have misused the mouse or responded randomly on some trials. However, contrary to this hypothesis, we found that the physical properties of false reports were highly similar to those of correctly reported fixations and followed the subject's search strategy. Also, false reports contributed to the variance of the total response time suggesting that they were somehow related to the objective behavior. We tested two alternative hypotheses that could explain such results. First, it is possible that subjects were using the time they spent doing the search task to infer part of their subjective report. False reports would reflect their attempt to complement their subjective reports with locations chosen a posteriori in the display (i.e. unrelated to the motor behavior). Alternatively, false reports might reflect covert shifts of attention. Along the scan path, observers would, on some occasions, keep their eyes fixed at a location while shifting their attention to another one. In an attempt to separate these hypotheses, we measured the duration of fixations temporally close to unmatched movements and compared them to the one close to reported fixations. We found the former to be longer than the latter which suggests that at least part of false reports could reflect covert attentional shifts during overt visual search. Note that these two interpretations are not exclusive. Over trials, a part of the false reports might correspond to erroneous subjective reports and another part could reflect covert shifts of attention.

Although our interpretation is still speculative, it is compatible with the premotor theory of spatial attention (Rizzolatti, Riggio, Dascola, & Umilta, 1987a; Rizzolatti, Riggio, & Sheliga, 1994; Sheliga, Riggio, & Rizzolatti, 1994), according to which top-down orienting of spatial attention originates from the same cortical circuits as saccade planning. There is evidence that spatial attention is accompanied by saccade preparation but not necessarily by saccade execution (Belopolsky & Theeuwes, 2012; Posner, Snyder, & Davidson, 1980; Rizzolatti, Riggio, Dascola, & Umilta, 1987b), and that covert attentional movements occur during serial search tasks (Buschman & Miller, 2009; Corbetta et al., 1998; Purcell, Schall, & Woodman, 2013). Other eye-tracking studies suggested that subjects can look at a distractor stimulus without actually processing it (Roebers, Schmid, & Roderer, 2010). Our findings provide further insights into how covert and overt attention might interplay during visual search. The scan path of an observer might consist of a programmed sequence of eye movements, most of which would be actually executed while a minority would be replaced by covert shifts of attention.

Our data are compatible with serial models in which attention goes sequentially through a series of location (Treisman, 1988; Wolfe, 2007; Woodman & Luck, 1999). The Guided Search model, for instance, proposes that serial attention is guided through the visual display by parallel processes that select a subset of items likely to contain the target (Wolfe, 2007; Wolfe, Cave, & Franzel, 1989). In agreement with guided search, we found that reported and real eye fixations were preferentially directed toward items of the target color. This observation is consistent with the idea that parallel processing boosts items that share features with the target (Bichot, Rossi, & Desimone, 2005; Melcher, Papathomas, & Vidnyanszky, 2005) and guides attention and/or eye movements close to them (Motter & Belky, 1998; Wolfe, 2007; Zelinsky, 2008). It is, however, incompatible with models proposing that visual attention randomly chooses and processes one item at a time, as originally envisioned in Feature Integration Theory (Treisman & Gelade, 1980). Our subjects' reports and eye movements also do not fit with the view that all items are processed in parallel, with attentional resources shared between them (Theory of Visual Attention; (Bundesen, Habekost, & Kyllingsbaek, 2005)) although we cannot exclude that parallel processes contribute in part to the increase in response times as a function of display size.

Finally, past studies revealed that eye fixations can be directed to the centroid of a group of items in the display rather than to the exact location of a single item (Findlay, 1982; Zelinsky, Rao, Hayhoe, & Ballard, 1997), suggesting that the search might proceed by a recursive exploration of progressively smaller groups of objects until it surrounds only the target (Zelinsky et al., 1997). The objective behavior observed in our study might be compatible with this hypothesis, but subjective reports suggest an alternative interpretation: during overt serial search, the eyes can be directed to the centroid of a group of objects while attention can be covertly shifted to a single object. Interestingly, in their second experiment, Zelinsky et al. (1997), made a remark that is consistent with our interpretation: the subjects covertly searched for a target object without moving their eyes (less than 1.5% of trials had saccades) but still reported a "strong subjective impression of moving their eyes" (Zelinsky et al., 1997, p. 451). It is plausible that this subjective impression corresponded to the subjects' introspection of moving their attention instead of their eyes.

5. Conclusions

In conclusion, although subjective reports are only partially accurate, the information they provide is tightly linked with the subject's objective behavior within a single trial. Observers can, at least to some extent, reflect upon the chain of cognitive events during task execution. The comparison between objective and subjective behavior suggests that overt and covert attention could be interlaced during serial search: sometimes observers would move their eyes to a spatial location and sometimes they would keep their eyes still while shifting only their attention. Perhaps the most exciting aspect of the present study is its potential to pave the way for future studies by distinguishing these previously covert events. More generally, we demonstrate here that introspection can be both an object and a method of investigation. Introspection is a cognitive operation that human observers readily perform and, as such, needs to be explored in detail. In addition, once carefully controlled, subjective reports might reveal information on human cognition that remains beyond the reach of standard objective measures.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.concog.2014.11.007.

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