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The speed of visual recognition memory

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Two processes are thought to support visual recognition memory (VRM): Familiarity and recollection. The former is generally considered to be faster. However, the relationship between the precise onset of the two processes is unclear. Here, we use a novel paradigm, the SAB (Speed and Accuracy Boosting procedure) that constrains participants to use their fastest strategy and provides a continuous distribution of their reaction times. We show that fast recognition occurs as early as ~370 ms, a limit that appears incompressible whatever types of stimuli were used. In a second experiment, running the SAB in conjunction with a modified version of the remember/know paradigm, we show that responses up to ~420 ms are based solely on familiarity. These time limits of 370 ms and 420 ms provide strong constraints on the neural mechanisms underlying VRM and suggest that the fastest, familiarity-based, responses could rely on the visual ventral stream only.

Keywords: Faces; Objects; Reaction time; Visual recognition memory; Visual ventral stream.

Visual recognition memory (VRM) is the ability to judge if an item has previously been encountered. This ability is thought to rely on the contribution of two distinct processes: Familiarity and recollection (Mandler, 1980; Yonelinas, 2002). Familiarity is based on the mere feeling

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that an item has previously been experienced. Recollection-based recognition on the other hand relies on the retrieval of specific contextual details. Familiarity, which is reported to be automatic and rapid, in contrast to the effortful and times consuming recollection, could represent an evolutionary advantage to generate efficient and rapid reactions to novelty (Brown & Aggleton, 2001).

Knowledge about the general properties of the human VRM system is important. For example, the fact that humans can store and recognize thousands of pictures in a few hours (Brady, Konkle, Alvarez, & Oliva, 2008; Standing, 1973) suggests that it is a critical cognitive system and raises questions regarding the underlying mechanisms (Bogacz, Brown, & Giraud-Carrier, 2001). If speed is such a specific feature of VRM, its speed should be known. To our knowledge, however, the exact speed of VRM, and of familiarity and recollection, remains largely unknown.

Distinguishing the effects of repetition and list length on responses latencies, (Juola, Wood, & Atkinson, 1971) suggested for the first time that two processes could contribute to recognition memory. In the 1980s–1990s, the Speed–Accuracy Tradeoff (SAT) procedure supplied an interesting value regarding the speed of recognition memory: The x-intercept, where the fitted SAT curve starts to rise above chance. This intercept was reported in item-recognition tasks to be between ~350 ms and ~600 ms (Boldini, Russo, & Avons, 2004; Boldini, Russo, Punia, & Avons, 2007; Dosher, 1984; Gronlund, Edwards, & Ohrt, 1997; Gronlund & Ratcliff, 1989; Göthe & Oberauer, 2007; Hintzman & Caulton, 1997; Hintzman, Caulton, & Levitin, 1998; Hintzman & Curran, 1994, 1997; McElree, Dolan, & Jacoby, 1999; Mulligan & Hirshman, 1995; Rotello & Heit, 2000). However, a rather large variability is reported and these SAT studies were based on word recognition. To our knowledge, no SAT study was ever run using visual stimuli.

Recollection has also been studied using the SAT procedure in source- and pair-recognition tasks. Corresponding x-intercept was reported to be between ~460 and ~650 ms (Dosher, 1984; Gronlund & Ratcliff, 1989; Gronlund et al., 1997; Hintzman & Caulton, 1997; Hintzman et al., 1998; Hintzman & Curran, 1994; Mulligan & Hirshman, 1995; McElree, Dolan, & Jacoby, 1999; Rotello & Heit, 2000), suggesting that recollection slows down RT. Again, this is a rather large variability. Moreover, performance at the x-intercept is still at chance and, as SAT studies does not supply a continuous distribution, the first time at which performance is reliable has not been assessed.

In addition, some studies have also shown that recollection can contribute to the fastest responses (Yonelinas & Jacoby, 1994), and it have been suggested that recollection could also rely on automatic processing (Gardiner, Konstantinou, Karayianni, & Gregg, 2005; Gardiner, Ramponi, & Richardson-Klavehn, 1999; Konstantinou & Gardiner, 2005). Hence, it is not entirely clear whether the speed of recollection is the same or slower than the speed of familiarity. Recently, Starns, Ratcliff, and McKoon (2012) evaluated how models of recognition memory could account for RT data in a yes/no paradigm, using an implementation of the diffusion model (Ratcliff, 1978). However, again, no exact prediction on the speed of familiarity and recollection were made.

Interestingly, electrophysiological data could lead to some hypotheses on the speed of familiarity and recollection. Scalp-EEG studies have reported two components associated respectively with familiarity and recollection: The mid-frontal negativity FN400 (300–500 ms) and the central-parietal LPC (Late Positive Component, 500–800 ms) components (Curran, 2000; Rugg & Curran, 2007). Thus, familiarity should preceded recollection, and, since the time necessary to make a decision and motor response is around 110 ms (Kalaska & Crammond, 1992; VanRullen & Thorpe, 2001), the fastest familiarity-based responses should start at ~410 ms and the fastest recollection-based responses at ~610 ms.

The aim of this study was to identify the exact speed of the fastest accurate VRM responses in order to characterize a property of VRM which appears important to investigate underlying processes. Because, as outlined earlier, the SAT procedure does not identify precisely the onset of the fastest VRM latencies (since the x-intercept is still at chance and no continuous distribution can be computed), we developed a new experimental paradigm in order to empirically measure the first time at which performance is reliable (i.e., the minimal behavioural RT, or minRT; see Rousselet, Macé, & Fabre-Thorpe, 2003). The Speed and Accuracy Boosting procedure (SAB), which allows plotting a real distribution of the data, is designed to oblige participants to use their fastest strategy in order to minimize variations of minRT.

In Experiment 1, the SAB was used for three types of visual stimuli (abstract patterns, concrete objects, and famous faces) for different response deadlines (600, 500, and 400 ms) in order to identify a lower bound to the speed of VRM. In Experiment 2, we assessed which types of subjective experience (familiarity/recollection) are associated with the fastest responses, in order to compare the speed of familiarity and recollection.

MATERIALS AND METHODS

Experiment 1: The SAB experiment

Participants. A total of 23 participants (11 women) were included in this study (mean age: 25.2+/−3.0 [21–34], all right-handed). For each condition, the number of participants is reported in Table 1. All participants had normal or corrected-to-normal vision.

TABLE 1
Performance of participants on the SAB in all conditions

Conditions	Number of participants	Number of stimuli targets/distractors	Accuracy (d') Across participants Mean	SEM	Across trials	Minimal reaction time Across participants Mean	SEM	N	Across trials
Experiment 1									
RDL at 600 ms									
ABS	15	120/120	1.23	0.12	1.14	428.0	7.7	15	390
OBJ	15	120/120	2.24	0.18	2.05	428.0	5.2	15	390
FF	15	120/120	1.11	0.15	1.02	431.5	12.7	13	400
RDL at 500 ms									
ABS	9	90/90	0.75	0.15	0.72	424.3	11.2	7	400
OBJ	10	90/90	1.57	0.14	1.48	413.3	3.9	9	370
FF	7	90/90	0.19	0.07	0.18	420.0	22.7	2	*ns*
RDL at 400 ms									
ABS	6	90/90	0.09	0.05	0.07	*ns*	*ns*	0	*ns*
OBJ	6	90/90	0.21	0.12	0.19	390.0	0.0	2	*ns*
Experiment 2									
RDL at 600 ms									
OBJ	19	120/120	2.24	0.11	2.12	432.6	4.6	19	410

ABS = condition using abstract patterns. OBJ = condition using concrete object. FF = condition using famous faces. RDL = response deadline. *ns* = not significant. SEM = standard error of the mean. N = number of participants for whom a minRT could be computed.

Experiments. The experiments included three or four blocks of a recognition memory task. Each block began with a study phase, in which stimuli (30 targets) were presented one by one, in the centre of a grey screen. Participants were explicitly instructed to remember all single-trial stimuli. Each stimulus was presented at least 3 s, before participants could press a button to move on to the next trial. The study phase was followed by an interference phase consisting of the presentation of 3 minutes of a cartoon. The test phase ensued during which participants had to recognize the stimuli that were presented earlier, intermixed with new stimuli (30 distractors) that they had never seen before. Each experiment was preceded by two training blocks (for one training block: 10 stimuli studied, to be recognized among 10 new). For the famous faces experiment, only the test phase was run.

The SAB procedure. We introduce here a new procedure called the Speed and Accuracy Boosting procedure (SAB; Figure 1). Based on a classical go/no-go task, the SAB constrains participant to answer before a response deadline, e.g., before 600 ms following stimulus onset. If a Go-response is

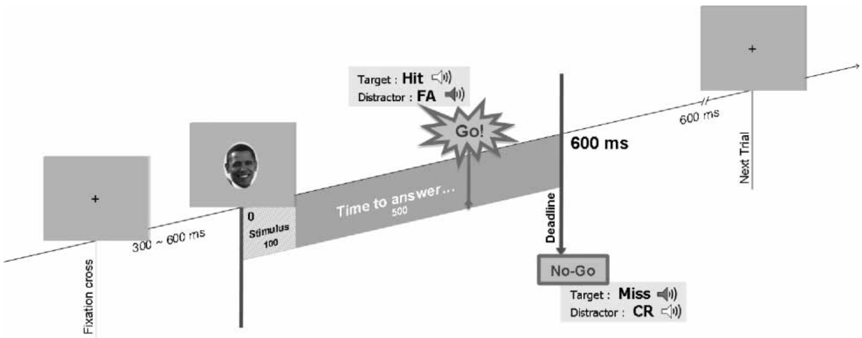

Figure 1. The SAB. Illustration of the test phase with a response deadline at 600 ms. Participants had to give their go-response within the 600 ms following the onset of a trial.

made before this response deadline, an audio-feedback is played, positive if the item was a target (hit), negative if the item was a distractor (false-alarm). If a No-Go response is made, an audio-feedback is given at the response deadline, positive if the item was a distractor (correct no-go), or negative if the item was a target (omission). Hence, participants are forced to answer quickly or else a negative feed-back will be played if no response was provided during the delay and a target was presented. Before each item presentation, a fixation cross is displayed for a pseudo-random time between 300 and 600 ms. Items were presented for 100 ms (comprised in the response deadline). It is expected that the response deadline boosts speed while the audio feedback boosts accuracy. The SAB is a highly demanding task, in particular for short response deadlines. Subjects therefore have to be strongly motivated and implicated in the task.

Conditions. Experiment 1 was run using three different types of stimuli: Abstracts patterns (ABS), pictures of objects (OBJ), and famous faces (FF) (see later and Figure 2). Within each experiment, different response deadlines were used: 600 ms (all three types of stimuli), 500 ms (all three types of stimuli), and 400 ms (ABS and OBJ only). The initial deadline of 600 ms was chosen after preliminary tests and because it had already been used in a related experiment (Ellis, Young, & Flude, 1990). Table 1 presents the number of participants used in each condition.

Stimuli. Abstract patterns ($n = 720$) were chosen from different internet databases. They were colourful clip-arts (200×200 pixels, visual angle: $\sim 4.5 \times 4.5$ degrees) as varied as possible and difficult to verbalize, in particular when several are seen in a row. All pictures of objects ($n = 720$) were colour photographs of real objects ($mean = \sim 183 \times 199$ pixels, $SD = \sim 131 \times 127$ pixels; visual angle: $\sim 4.1 \times 4.5$ degrees, $SD = \sim 2.9 \times 2.9$), without any context, as varied as possible and a priori easy to verbalize using a single word. In each block, half were biological and half were man-made. Famous faces ($n = 140$) were selected as the 140 most recognized famous faces from a large database that had been used in previous experiments in participants of the same age as in this experiment (Barragan-Jason, Lachat, & Barbeau, under review). Distractors for famous faces were unknown faces ($n = 140$) used in the same experiments. They were chosen so that unknown faces "looked like" they could be famous. Photographs were in greyscale and were matched in face size, luminance, and contrast compared to the famous faces set. All faces were cut out with the same oval (286×400 pixels, visual angle: $\sim 6.4 \times 9.0$ degrees) from their context.

Set-up. Participants sat in a dimly lit room, at 90 cm from a computer screen piloted by a PC. Image presentation and behavioural responses recordings were carried out using the E-prime version 2 software. Participants responded to the stimuli by raising their fingers from an infrared response pad (Macé, Joubert, Nespoulous, & Fabre-Thorpe, 2009; Rousselet et al., 2003).

Minimal reaction times. The minimal behavioural reaction time (minRT) was computed by determining the bin at which correct go-responses ("hits") started to significantly outnumber incorrect go-responses ("false-alarms"), when dividing RT distributions into bins of the same width (see Bacon-Macé, Kirchner, Fabre-Thorpe, & Thorpe, 2007; Delorme, Rousselet, Macé, & Fabre-Thorpe, 2004; Kirchner & Thorpe, 2006; Macé et al., 2009; Rousselet et al., 2003). For each condition, the analyses were performed either across trials (by pooling together all trials from all participants for a given condition) and across participants (mean of all participants' individual mean performance). Across trials analyses have been used in previous studies (Macé et al., 2009; Rousselet et al., 2003) and are like building a "metaparticipant", reflecting the performance over all the population. MinRTs across trials were computed using 10 ms time bins. The minRT was determined as the middle of the first bin that was significant, χ^2-test, $p < .05$, followed by at least two significant consecutive bins. Across participants, in order to accommodate for the lower statistical power than across trials data since there were fewer trials, we used 30 ms time bins and a Fisher's exact test ($p < .05$). It was not always possible to calculate a minRT for each participant in the most difficult conditions (small response deadline). This information is indicated in Table 1. A minRT over all conditions was also computed pooling all trials of all participants from the eight conditions together using the same criteria that in previous across trials analyses. Because of the small number of participants, nonnormality distribution and possible outliers, all statistical comparisons between conditions were nonparametrical (Kruskal-Wallis, Mann-Whitney U, and Wilcoxon tests). All statistical analyses were two-tailed.

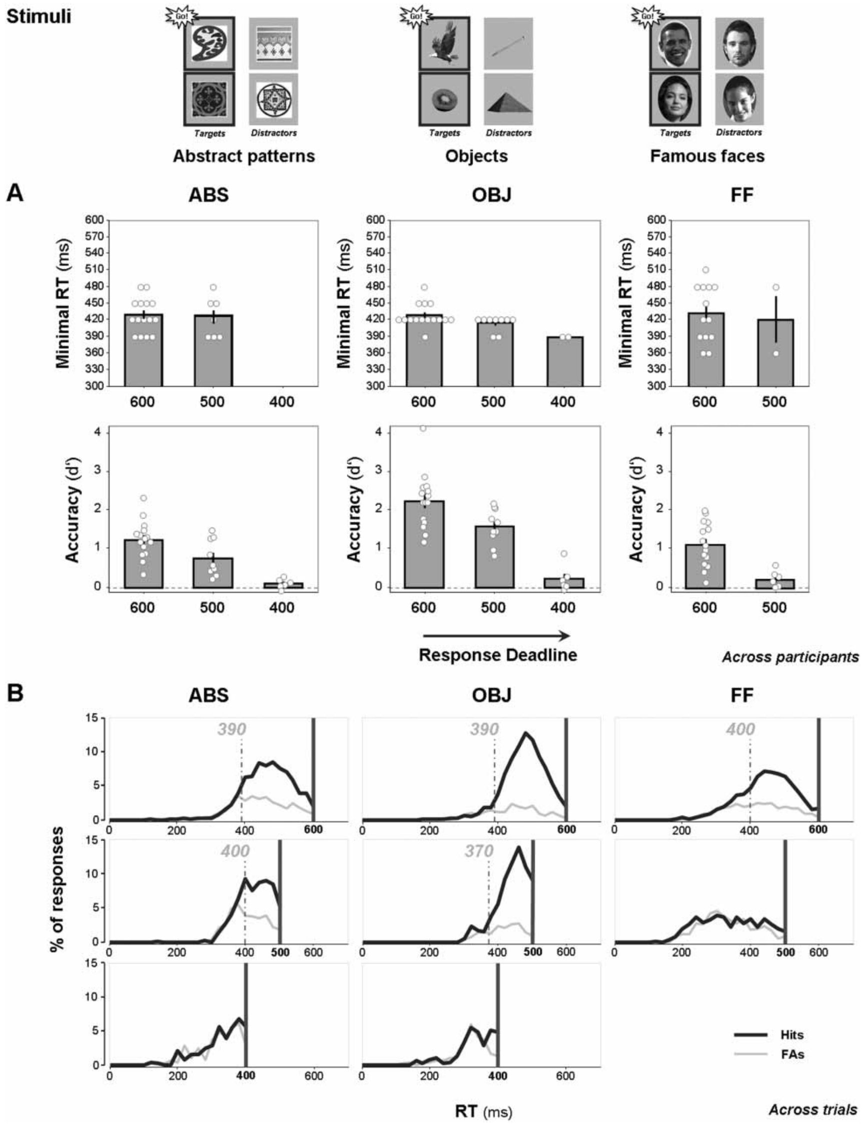

Figure 2. Sample of stimuli used: ABS = abstract patterns, OBJ = concrete objects and FF = famous faces conditions. (A) Results across participants. Each circle represents the performance of a participant according to different response deadlines. (B) Results across trials. Distribution of hits and false alarms. The dotted vertical line indicates the minRT, the bold vertical line the response deadline.

Regarding the famous faces, the first one is a photograph of Barack Obama, taken by egadapparel on Flickr, used under creative commons 2.0 (http://creativecommons.org/licenses/by-sa/2.0/), made available by Fotopedia. The second one is a photograph of Angelina Jolie, taken by World Economic Forum on Flickr, used under creative commons 2.0, made available by Fotopedia.

The two other faces are taken from our personnel database, used by permission of the model.

Experiment 2: Subjective experience accompanying go-responses in the SAB

Participants. 19 participants (mean age: 23.6+/−2.0, 14 women, 18 right-handed) underwent this modified version of the SAB. All participants had normal or corrected-to-normal vision.

Experiment. In order to evaluate the type of subjective experience (e.g., familiarity or recollection) accompanying responses in the SAB, we used a modified version of the remember-know-guess procedure in order to provide more choice for participants. Indeed, together with studies indicating that there can be different categories of recollection or familiarity (e.g., Montaldi, Spencer, Roberts, & Mayes, 2006; Peters, Daum, Gizewski, Forsting, & Suchan, 2009), preliminary investigations indicated that participants do not easily categorize their subjective experience as "remember" or "know" but that they spontaneously used other reports such as "I made a go-response because I recognize this small red triangle in the stimulus".

Four blocks of 30 trial-unique stimuli (OBJ) had to be learned and then recognized among 30 distractors. The paradigm was on all points similar to the SAB procedure except the following. On a proportion of one out of three go-responses (pseudorandomized), the feedback was not given but a question was presented instead: "In order to provide your response ...: (R1) "did you "remember" details from an external event that occurred during the item encoding? (e.g., a loud event occurring in the corridor)"; (R2) "did you "remember" details from an internal event that occurred during item encoding? (e.g., a particular thought or memories that popped-out looking at this item); (F1) "did you "notice" a particular intrinsic detail of the item, that you had already noticed during encoding? (e.g., a particular feature, odd or nice, that caught your attention at the first presentation of the item)"; (F2) "did you "know" that you had previously seen this item, with a mere feeling of familiarity, but without recollecting any particular details of any kind?"; (G) "did you just respond guessing, without truly knowing the answer?"; (FA) "did you made a false alarm?" Participants were explicitly asked to report which type of subjective experience they had *before* answering. A training session to familiarize participants with these different choices took place before the four blocks.

Minimal reaction times. MinRTs were computed using 10 ms time bins comparing the hits of each type of response against the false alarms made for each type of response. Significance was assessed using a two-tailed χ^2-test and set to $p < .05$ for at least three consecutive bins. The minRT was determined as the mid of the first bin.

RESULTS

Experiment 1: Using the SAB for different stimuli and response deadlines

For each condition, both accuracy and speed were computed, across trials and across participants. Details of the results are presented in Table 1 and Figure 2.

Accuracy. Using a response deadline at 600 ms, participants showed good accuracy for the three types of stimuli although OBJ were better recognized than ABS, Mann-Whitney test, $U(15) = 25$, $p < .001$, or FF, $U(15) = 23$, $p < .0001$. Using a response deadline at 500 ms, participants still presented correct accuracy for OBJ and ABS but FF recognition was difficult, $d' = 0.19$, SEM = 0.07, across participants and 0.18 across trials. Using a response deadline at 400 ms, the task could not be performed either for OBJ or ABS, Wilcoxon test against 0, $p > .1$ for both ABS and OBJ. Mann-Whitney tests showed that setting down the response deadline from 600 to 500 ms had a significant effect on the accuracy, which decreased for OBJ, $U(10) = 29$, $p < .01$, FF, $U(7) = 6$, $p < .001$, and showed a tendency for ABS, $U(9) = 35$, $p = .05$. Overall thus, setting down the response deadline from 600 ms to 400 ms had an effect on the accuracy of participants with accuracy falling down to chance-level when a response deadline of 400 ms was used.

Speed. Using a response deadline at 600 ms, almost all participants showed a significant minRT around the same mean of $\sim$430 ms for the three types of stimuli, Kruskal-Wallis test, $\chi^2(2, 40) = 0.025$, $p > .98$. Using a response deadline at 500 ms, most of the participants showed a significant mean minRT for ABS and OBJ of $\sim$420 ms, but only two participants showed a minRT in the FF condition. No minRT difference was observed between conditions, Kruskal-Wallis test, $\chi^2(2, 15) = 0.189$, $p > .90$. Setting down the response deadline from 600 to 500 ms had no significant effect on the minRT neither for OBJ, Mann-Whitney test, $U(9) = 43$, $p > .1$, ABS, $U(7) = 48.5$, $p > .7$, or FF, $U(2) = 11$, $p > .91$. Using a response deadline at 400 ms, only two participants showed significant minRT for OBJ (both at 390 ms), while none did for ABS.

What is the lower bound for recognition memory?. In this section, we assessed whether a lower bound for VRM could be identified. First, pooling all trials of all participants from the eight recognition memory conditions lead to a minRT of 370 ms (Figure 3A). Second, none of the eight conditions show minRT under this value across trials. Third, across participants, three participants had a minRT at 360 ms (for FF) and 13 participants had a minRT at 390 ms (seven for ABS, three for OBJ, three for FF) (Figure 3B).

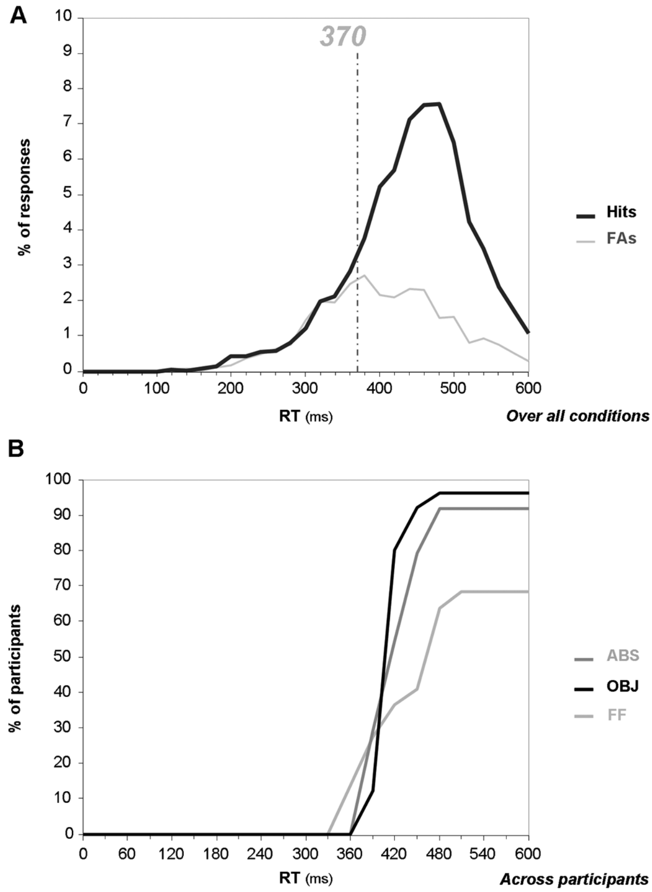

Figure 3. (A) Distribution of Hits and FA RT (bins of 10 ms) are plotted across trials over all conditions. MinRT is at 370 ms. (B) Cumulated percentage of participants who present a minRT across time. Here, for each category of stimuli, conditions using a response deadline at 600 ms and at 500 ms were pooled together.

Experiment 2: Subjective experience accompanying responses

Global results of the SAB (*d′* and minRT) in Experiment 2 are presented in Table 1. Comparing data from the SAB in Experiment 1 (OBJ with response deadline at 600 ms) and data from the SAB of Experiment 2, no difference was observed in accuracy, between *d′* of participants, Mann-Whitney test, $U(15) = 142$, $p > .9$, or minRT, between minRT of participants, Mann-Whitney test, $U(15) = 117$, $p > .3$. In addition, we computed the distribution of cumulated *d′* of each participant. Again, no significance was observed between both tasks in any bin of 10 ms, Mann-Whitney test, $U(15) > 115$,

$p > .2$. This indicates that despite the modification of the SAB procedure, accuracy, and minRT were comparable between both experiments.

Figure 4A presents the distribution of each type of subjective experience. "R1" responses were not reported by any participant. All "FA" responses were reported when distractors were presented. No difference was observed between the number of hits and false-alarms reported as "G", Wilcoxon signed-rank test, $W(7) = 10$, $p > .45$. No false-alarm was reported as "R2", nor as "F1". Some were reported as "F2"; however, less than hits: "F2", $62.8 +/- 14.8\%$ for hits vs. $1.7 +/- 2.5\%$ for false alarms, Wilcoxon

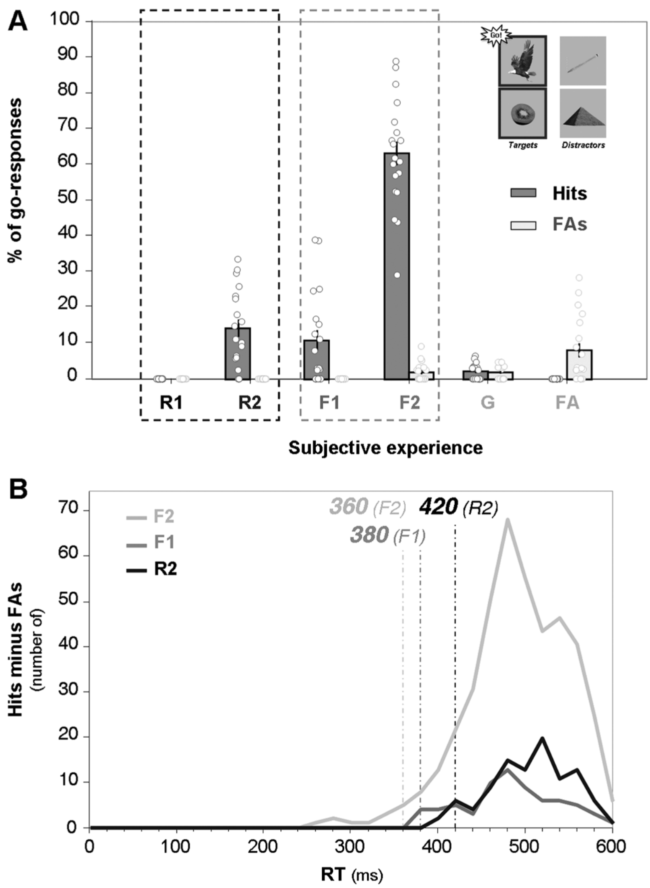

Figure 4. (A) Proportion of the type of subjective experience reported for each participant (circles). The histogram represents the mean and the vertical lines the SEM. (B) Distribution across trials of the RTs (hits minus FAs) according to the type of subjective experience. MinRT for each distribution are indicated as a vertical line.

signed-rank test, $W(19) = 190$, $p < .0001$. Overall, there were many more "F2" than other answers, $W(19) = 190$, $p < .0001$ for all comparisons.

MinRT were computed for "F2" (360 ms), "F1" (380 ms), and "R2" (420 ms) (Figure 4B).

DISCUSSION

The aim of the present study was to measure the speed of the fastest accurate responses that indicated correct visual recognition of previously exposed stimuli. For participants to use only the processes that are strictly necessary to make the first accurate response, a novel paradigm, the SAB, that constrains participants to answer as fast as possible and allows computing a real distribution of hits and false alarms, was developed. The main results of this study are that (1) VRM shows a lower bound around 370 ms, (2) such speed appears to be incompressible, and (3) the fastest responses (up to ~420 ms) are based on familiarity only. In the following discussion, we provide evidence that the identification of these time limits is important for a better understanding of VRM.

A lower bound for VRM

To identify a lower bound to the speed of VRM, we successively set down the response deadline to 600, 500, and 400 ms. Interestingly, accuracy decreased with lower response deadline but mean minRTs across participants were not much modified whatever the category of stimulus. This suggests that VRM speed cannot, or only marginally, in these conditions, be faster. In Experiment 1, converging evidence across participants and trials suggested a lower bound for VRM around 370 ms (Figure 2A across trials and 2B across participants). Experiment 2, carried out in an independent set of participants, supports the idea that 370 ms is a reasonable approximation of the lower bound of VRM (Figure 3).

The ABS stimuli were complex, difficult to verbalize and rather resembling each other. MinRTs in this condition was only slightly slower (390–400 ms) than for OBJ stimuli, which were all different objects, simple and easy to verbalize. Furthermore, although faces are usually considered as complex stimuli (i.e., perceptual interstimulus variance is low), recognizing famous faces among unknown ones did not lead to longer minRTs, which suggests that the speed of VRM is only marginally affected by stimulus complexity. It could have been that a larger number of trials could have led to shorter minRTs. However, only a small difference was observed between the first minRTs across participants (360–390ms) and across trials (370–390ms) suggesting that accurate responses before 370 ms are marginal. Our proposal here is that the 370 ms time limit may be a reasonable approximation of the fastest accurate VRM RTs.

There is converging evidence that the 370 ms lower bound found in this study is plausible. This limit falls within the lower limits estimated from the SAT studies, as briefly reviewed in the introduction (expected between 350 and 600 ms). Interestingly, similar results were recently reported using personally familiar faces, leading to a minRT of 380 ms ($N=17$; Ramon, Caharel, & Rossion, 2011). Third, the study by Barragan-Jason, Lachat, and Barbeau (under review) that used the same famous face stimuli reported a minRT of 390 ms across all trials ($N=31$), comparable to the minRT of 400 ms found in the present study. It has to be mentioned that this study used a simple go/no-go paradigm. Although the participants were requested to answer as quickly as they could, no response deadline nor feedback was provided. The range of minRTs found in Barragan-Jason et al.'s study was 390–720 ms, whereas it was 360–480 ms in the present study, hence demonstrating the usefulness of using time constraints. Also, the fastest minRT found in individual participants was 390 ms in the Barragan-Jason et al.'s study, which matches the latencies found in the present study (360 ms using 30 ms bins in both studies). Therefore, although minRTs across participants were overall faster in the present study, the SAB did not dramatically decrease the minRTs further supporting the idea that it had reached a lower bound.

Conditions under which the 370 ms lower bound is valid

Importantly, we propose that this 370 ms lower bound applies only to bottom-up VRM task such as that used in the present study. Most classical recognition memory tasks, such as the Recognition Memory Task (Warrington, 1984) or the face recognition memory task of the WMS-III (Wechsler, 2001) actually implicitly rely on bottom-up recognition. Such paradigm has been extensively used in order to study amnesia in both animals and humans, starting with the famous patient HM (Aggleton et al., 2005; Barbeau et al., 2005; Barbeau, Pariente, Felician, & Puel, 2011; Bastin et al., 2004; Bowles et al., 2007; Holdstock et al., 2008; Milner, 1972; Mishkin & Delacour, 1975). Bottom-up recognition tasks refer to tasks in which (1) the target has to be identified within a relatively large set of possible targets; (2) no evidence about the target can be preactivated before the recognition phase, which could boost speed through top-down processes; (3) targets are trial-unique during the recognition phase (or repetition would activate perceptual and conceptual fluency); and (4) some delay is applied between encoding and recognition so that recognition is based on long-term memory. Top-down recognition memory tasks are different from bottom-up recognition memory tasks in that there is only one or a limited number of targets (e.g., recognizing different pictures of Barak Obama within a set of distractors). Subjects can consequently preactivate diagnostic features of the target items, which yield much shorter RTs (i.e., around 220 ms for one target stimulus; Delorme et al., 2004). To some extent, top-down recognition can be compared to the case of searching for the presence of a friend in a scene. On the other hand, bottom-up recognition can be compared with the ecological situation of walking in the street and unexpectedly bumping into an acquaintance. The minimum reaction time in this condition would, according to our data, take at least ~370 ms. Again, the present results apply only to classic recognition memory paradigms as have often been used in psychological and neuropsychological studies (reviewed in Yonelinas, 2002).

There is a "grey zone" concerning the number of items that can be preactivated before the recognition phase (and maintained throughout this phase) so that it can speed up recognition through top-down processes, although it is probably related to working memory capacity. We are not aware of any suitable study on this issue if complex, trial-unique, single-items are used such as objects or faces. In particular, such a study would have to disentangle the contribution of conceptual and perceptual fluency (e.g., avoid repetition of items) and top-down processes. We make the hypothesis that the number of items that can be preactivated before the recognition phase is much lower than the number of items used in our study. We used 30 items for the object and abstract pattern conditions, which is well above working-memory capacity. Importantly, the set of possible targets was even much larger in the famous face condition since subjects know, presumably, hundreds or more famous faces. Consistently, the famous faces condition yielded to similar minRTs than the object and abstract pattern conditions.

Wolfe (2012) recently showed that the relationship between the memory set size and mean RTs is logarithmic in visual search tasks (in which one of previously memorized targets has to be detected within a set of objects presented in a visual display. Interestingly, a visual set size of one corresponds to the condition of our paradigm (one target or one distractor is presented each time on the screen). The mean reaction time varied from ~500 to ~800 ms (estimated from Figure 1) when the memory set size was increased from 1 to 100 objects. In this experiment, no time constraint was used and the focus was on mean rather than minimal reaction time. It is therefore difficult to compare the results of the present study directly to that conducted by Wolfe. However, this prompts for a comment on familiarity and recollection. It is unclear in the findings reported by Wolfe whether it is recollection or familiarity that shows this logarithmic relationship. Given that subjects were not given any time constraint, it could be that their responses were mostly based on recollection (in order to reduce false alarms) and that the greater the memory set size, the more recollection would be needed to verify the response. By contrast, familiarity (which is the process on which the SAB mostly relies, see later) could be independent of the memory set size given that familiarity could arise simultaneously to the visuoperceptive processes necessary to process the item (Cowell, Bussey, & Saksida, 2010). This hypothesis clearly merits further study.

The SAB and the SAT

Similarly to previous studies on visual categorization (Bacon-Macé et al., 2007; Delorme et al., 2004; Fabre-Thorpe, 2011; Joubert, Rousselet, Fize, & Fabre-Thorpe, 2007; Macé et al., 2009; Rousselet et al., 2003; VanRullen & Thorpe, 2001), the present study has been designed to evaluate the minimal reaction time (minRT) required to make a decision that an item has previously been seen. The minRT corresponds to the RT at which participants start to respond with above-chance accuracy (Kirchner & Thorpe, 2006; Rousselet et al., 2003). It reflects the speed of the processing that is *strictly* necessary to make the first accurate behavioural response.

It is noteworthy that the SAB allows computing a speed that is different from the speed calculated from the intercept of SAT studies. In SAT studies, the lag at each trial (at which a signal demanding an immediate response is given) is chosen pseudorandomly among the different lags that were preset for the experiment. The delay before each signal is unknown by the participant, who has to react appropriately at each trial. It is therefore likely that the RTs computed from SAT studies include processes related to inhibition removal. A notable difference also is that the SAB supplies a continuous distribution of RTs over the whole range of time. In contrast, the SAT gives clusters of RTs after each lag, supplying a distribution somewhat like a step function, which makes the assessment of the first reliable responses more difficult. Of note, even studies that have asked for responses before the response deadline have not reported distributions of RTs or minRTs (Gardiner, Konstantinou, Karayianni, & Gregg, 2005; Jacoby, Jones, & Dolan, 1998; Konstantinou & Gardiner, 2005). Finally, an important distinction between these paradigms is the use of a go/no-go task in the SAB procedure compared with a yes/no tasks in many SAT experiments (however, see Boldini et al., 2004, 2007, who used a go/no-go paradigm). Yes/no tasks are expected to yield longer RTs due to the necessity to perform (1) a supplementary "no" decision, and (2) a supplementary competition due to the choice of the motor effector (Bacon-Macé et al., 2007). Importantly, recognition memory in daily life is rather like in go/no-go paradigms when a single stimulus is recognized and triggers appropriate behaviour. In this context, go/no-go paradigms may reflect more ecological processes.

VRM: A lengthy process?

Rapid visual categorization tasks at the superordinate level (e.g., animal/ nonanimal) yield minRTs around 260 ms (reviewed in Fabre-Thorpe, 2011). Here, we find that VRM tasks, that is visual processes at the individual item level, result in minRTs around 370 ms. This is a huge 110 ms increase. In this regard, it is surprising that bottom-up VRM requires, comparatively, such a long time, as such a system is thought to be an evolutionary advantage (Brown & Aggleton, 2001). This probably corresponds to different processes needed for visual processing at the individual level, but that are not for processes at the superordinate level, such as longer visual processing time (DiCarlo, Zoccolan, & Rust, 2012; Hochstein & Ahissar, 2002) and access to awareness (Danckert, Gati, Menon, & Köhler, 2007). A 370 ms lower bound indicates that there is a need to identify and characterize these additional processes.

Behavioural data is an upper bound for neuronal activity

In EEG studies, familiarity and recollection have been linked respectively with the mid-frontal negativity FN400 (peaking between 300–500 ms) and the central-parietal LPC (Late Positive Component peaking between 500–800 ms) components (Curran, 2000; Rugg & Curran, 2007). Here, using the SAB procedure, behavioural responses were elicited as early as 370 ms. How can these components be related to these rapid responses?

The lower bound of 370 ms found for the behavioural minRTs is an upper bound for the neural mechanisms underlying VRM. The neuronal time—included in the behavioural RTs—required for decision and motor response has been evaluated to be around 110 ms (~80–100 ms in the macaque; Kalaska & Crammond, 1992; VanRullen & Thorpe, 2001). Hence, the first neuronal differential activity between targets and distractors in recognition memory tasks should begin within a window between 240 and 260 ms after stimulus onset. This is earlier than the time-window of the FN400. Interestingly, however, studies in humans using scalp-EEG recordings indeed report a first *differential* activity in VRM tasks around 250 ms poststimulus (Bentin & Deouell, 2000; Eimer, 2000; Maillard et al., 2011; Pfütze, Sommer, & Schweinberger, 2002; Puce, Allison, & McCarthy, 1999; Schweinberger, Pfütze, & Sommer, 1995). Therefore, this 370 ms limit in fact also appears to be related to the neuronal processes underlying recognition memory.

This has crucial implications. It is likely that this 250 ms differential neural activity relies on neocortical areas (Barbeau et al., 2008; Maillard et al., 2011). Furthermore, it appears that hippocampal responses are in general more delayed than neocortical responses (Barbeau et al., 2008; Mormann et al., 2008; Trautner et al., 2004). This would suggest that the fastest responses (at least "F2" responses before 420 ms) could depend on neocortical activity rather than on the hippocampus, whereas whether behavioural recognition memory responses can depend on the neocortex only is unclear up to now (Barbeau et al., 2005, 2011; Bastin et al., 2004; Manns, Hopkins, Reed, Kitchener, & Squire, 2003; Mayes, Holdstock, Isaac, Hunkin, & Roberts, 2002). Further experiments are obviously needed to ascertain this hypothesis, and the SAB, in combination with real-time correlates of the neural activity such as EEG or MEG, may be an interesting tool with this regard.

The speed of familiarity and recollection

We used a modified version of the remember-know procedure, supplying participants with an enriched range of possible choices. We were interested in the subjective experience that participants had before they recognized the picture. The procedure was easily understood and appeared to be applied correctly. Indeed, "false alarms" were reported only on distractors; "guess" was reported for half on targets, and half on distractors; "feature-based recognition-F1", "familiarity-based recognition-F2", and "internal detail recognition-R2" were mainly reported on targets, with "F1" and "R2" never reported on any distractors as expected for high-confidence answers; "external detail recognition-R1" was never reported, probably because participants sat in a dimly lit room, door closed, with very rare events occurring outside. Moreover, the introduction of the modified RK procedure had no effect on performance, compared to the same task ran in the Experiment 1 (OBJ, with a response deadline at 600 ms). These results, which match expectations, suggest that it is possible to use the SAB concomitantly to our modified remember-know procedure.

The main type of awareness associated with recognition was a feeling of familiarity ("F2"), implying that most responses made in the SAB relied on this process. It was also the fastest, starting at 360 ms. Furthermore, in such a short time (less that 600 ms), our results show that "F1" and "R2" types of subjective experience are possible. Importantly, no go-responses was reported to be based on feature recognition ("F1") before 380 ms and on recollection ("R2") before 420 ms. This suggests that familiarity is about 60 ms faster than recollection.

The findings of the present study are consistent with the dual-process theory and the historical description of familiarity being rapid (Brown & Aggleton, 2001; Juola, Fischler, Wood, & Atkinson, 1971) and, in contrast with other findings (Yonelinas & Jacoby, 1994), imply that familiarity may contribute to recognition earlier than recollection. Furthermore, these findings for the first time, estimate with precision the behavioural onset of familiarity-based and recollection-based responses.

CONCLUSION

In sum, we report in this study that the fastest VRM responses can occur around 370 ms and that, up to around 420 ms, most accurate responses may be based on familiarity only. Such time limits can be used as constraints to identify the visual processes taking place during visual recognition memory in regard to current models of the visual ventral pathway (Cowell et al., 2010). They can also be useful to ascertain the respective role of neocortical structures and the hippocampus in recognition. Last, they may contribute to the debate around the models of familiarity and recognition (Wixted & Mickes, 2010). Eventually, they could be used as markers in assessing the consequences of diseases (Barbeau et al., 2004; Davidson, Anaki, Saint-Cyr, Chow, & Moscovitch, 2006; Didic et al., 2011; Guedj et al., 2010).

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