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Retrospective Cueing Mediates Flexible Conscious Access to Past Spoken Words

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Can we become aware of auditory stimuli retrospectively, even if they initially failed to reach awareness? Here, we tested whether spatial cueing of attention *after* a word had been played could trigger retrospective conscious access. Two sound streams were presented dichotically. One stream was attended for a primary task of speeded semantic categorization. The other stream included occasional target words, which had to be identified as a secondary task after the trial. We observed that cueing attention to the secondary stream improved identification accuracy, even when cueing occurred more than 500 ms after the target offset. In addition, such "retro-cueing" boosted the detection sensitivity and subjective audibility of the target. The effect was a perceptual one and not one based on enhancing or protecting conscious representations already available in working memory, as shown by quantitative models of the experimental data. In particular, the retro-cue did not gradually shift audibility but rather sharply changed the balance between fully audible and not audible trials. Together with remarkably similar results in vision, these results point to a previously unsuspected temporal flexibility of conscious access as a core feature of perception, across modalities.

Public Significance Statement
This study demonstrates that a cue presented after a sound has ended can still retrospectively trigger its conscious perception. As similar observations had been made in vision, we suggest that temporal flexibility of conscious access is a general and useful feature of perception.

Keywords: retro-cue, attention, consciousness, retro-perception, auditory perception

Supplemental materials: https://doi.org/10.1037/xhp0001132.supp

What is the temporal structure of our conscious mental life? While we may have a feeling of a continuous "stream of consciousness," with a timeline of mental events seemingly reflecting the timeline of physical events in the outside world, some influential theories on the mechanisms of conscious awareness suggest that these two timelines might be, in fact, partially disconnected (Dennett & Kinsbourne, 1992; Sergent, 2018; Sergent et al., 2013). The evidence for such a startling claim has, to date, only been reported for the visual modality. The objective of the present study is to test whether such findings generalize to audition. Temporal constraints are even more critical in audition than in vision, given the inherently fleeting nature of auditory events, thus it is of particular interest to assess whether a decoupling of conscious access from the timing of external events can occur in this modality.

Our experimental questions aim to extend the classic observation that performance on a perceptual task can be influenced by events occurring after the offset of the target stimulus. Perhaps the most famous examples of such findings relate to visual iconic memory experiments, as introduced by Sperling (1960). In his experiments, participants displayed better performance for reporting items in an array when a "retrospective" cue appearing after the stimulus indicated which random subset of the array they should report, compared to when no cue was presented and they had to report as many items as possible. This constituted a remarkable demonstration that performance could be influenced by attention even after the stimulus to be processed has disappeared. The interpretation provided was that the retro-cue facilitated the transfer of perceptual information from iconic memory to a more durable form of memory required at the time of the report. This led to the famous statement "more is seen than can be remembered," appositely summarizing the view that the retrospective cue acted on memory, and not on perception itself.

Since then, several other studies in vision have shown various forms of retro-cueing effects, notably extending these results to working memory (Griffin & Nobre, 2003; Landman et al., 2003). All of these experiments assumed that the retro-cue acted at a "postperceptual" stage, either decision or memory. Indeed, the

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This study was not preregistered. Data and Matlab scripts for analysis are available online (https://osf.io/ukhct/?view_only=3c85be6a5a1a49cd86c0beb1751cb90b).

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widespread theoretical framework to account for such results postulates that events occurring after the sensory processing stages, typically beyond 100–200 ms poststimulus, are totally unable to affect our conscious perception of the stimulus (Carrasco et al., 2008; Kinchla et al., 1995; Prinzmetal et al., 2008; Woodman et al., 2003). This postulate is often stated explicitly, as in the following citation: "If the cue comes after the stimulus, it cannot have any effect on the perception of the stimulus. Rather, effects from a cue that appears after the stimulus must reflect nonperceptual processes" (Prinzmetal et al., 2008, p. 1146).

Although this assumption seems reasonable, perhaps because it aligns well with common intuition, it is now challenged by theoretical and experimental arguments. Increasingly influential theories of consciousness propose that conscious perception does not occur during the initial buildup of representations within sensory cortices, but rather emerges at a later stage where sensory representations enter a "global workspace." The global workspace is identified as a wide network of areas beyond sensory cortices, within which information can be amplified, stabilized, and allowed to influence processors well beyond automatic processing routes (Baars, 1989; Dehaene & Naccache, 2001; Mashour et al., 2020; Sergent & Dehaene, 2004b; Sergent & Naccache, 2012). Experimentally, several neuroimaging results showed that the divergence between conscious and unconscious processing can occur quite late into the chain of information processing, beyond 250 ms poststimulus (Del Cul et al., 2007; Gaillard et al., 2009; Sergent et al., 2005, 2021). A logical but puzzling prediction of this framework is that conscious perception should be, to a large extent, desynchronized from the onset of external stimuli (Sergent, 2018). Even if a stimulus was not initially perceived, as long as sensory cortices hold some trace of this past stimulus, triggering postsensory mechanisms for conscious access should be able to trigger conscious perception of a past stimulus, retrospectively.

Behavioral correlates of such putative retro-perception have been found in a series of our own studies, in the visual modality. We designed protocols where memory load was intentionally reduced to a minimum, but where the limiting factor was perceptual (Rimsky-Robert et al., 2019; Sergent et al., 2013; Thibault et al., 2016; Xia et al., 2016). This was a critical difference from previous retro-cueing studies, which used stimuli that were complex but easy to perceive, so that memory load was likely the major limiting factor for performance (Vogel et al., 2005). Another critical difference was that we did not only measure objective performance, but we also collected participant's subjective report of visibility (Sergent et al., 2013). Such reports are integral to the long-standing literature on consciousness (Dennett, 1992; Sandberg et al., 2010; Sergent & Dehaene, 2004a). Specifically, in our visual experiments, the target was a single low-contrast stimulus (a Gabor patch) briefly presented to the left or to the right of fixation. This target could be preceded or followed by a cue (visual or auditory) that oriented the participants' attention either to the target's side or to the opposite side. We found that, even several hundred milliseconds after the disappearance of the stimulus, orienting attention to its past location substantially improved participants' ability to report its presence and its orientation. Importantly, the retro-cues did not induce a gradual increase in the visibility of targets, but instead increased the number of trials where the target was seen, in an all-or-none fashion. In other words, the retro-cues granted conscious access to past targets that would otherwise have remained unconscious.

This "retro-perception" effect has now been replicated in various experimental protocols by us and others (Rimsky-Robert et al., 2019; Sergent et al., 2013; Thibault et al., 2016; Xia et al., 2016). It is one of the few experimental arguments that allow contrast predictions from competing models of conscious access (Herzog et al., 2020; Lamme, 2003, 2006; Mashour et al., 2020; Sergent, 2018). However, to date, retro-perception has only been investigated in the visual domain, which is an obvious limitation, since current models of consciousness do not limit their scope to one single modality. Moreover, theoretical considerations suggest that if flexible conscious access to past events is useful for vision, it should be even more ecologically relevant to audition. Vision is a sensory modality for which the external information is relatively stable over time (O'Regan & Noë, 2001). Audition, in stark contrast, has to deal with external information that is by nature transient, so poststimulus perceptual processes could have an even stronger contribution to everyday hearing (Demany et al., 2010).

A case in point is the auditory scene analysis problem, a generic term to refer to our impressive ability to make sense of complex mixtures of sounds (see Snyder et al., 2012, for a review). A classic and typical scenario consists in following a conversation among several talkers, referred to as the "cocktail party problem" (Cherry, 1953). In a seminal study, Cherry played two different speech streams, simultaneously, to the two ears of participants and asked them to repeat the content of one of the streams. After performing this primary task, participants were asked to recall what they heard in the unattended ear. Cherry observed that participants were largely unable to recall the content of the unattended ear, being only aware of whether it consisted of speech or not (Cherry, 1953). These first results were complemented by later studies (Moray, 1959), showing, for example, that participants may even fail to notice a change of language on the unattended side (Treisman, 1964). Thus, a large portion of the acoustic stimulation seemed to have completely failed to reach conscious awareness when not attended.

Is the cocktail party effect susceptible to retro-cueing, or, in other words, can seemingly lost words be recovered when attention is reoriented after the end of the word? Only a small number of studies have used retro-cueing in auditions (Backer & Alain, 2012; Chan & Alain, 2019, 2021; Lim et al., 2015). One example is an auditory equivalent of iconic memory experiments, where multiple sounds were played simultaneously from different locations (Backer & Alain, 2012). Participants were instructed to compare the spatial location of a subsequent probe with its original source in the auditory scene. Backer and Alain showed that cueing the to-be probed object during the retention interval improved the correct detection of a change in the location of the sound. Backer and Alain proposed two mechanisms supporting this attenuation of "change deafness": representation enhancement in auditory short-term memory and reduction of the memory load during the retention interval. Similarly, all the other retro-cueing effects observed so far in the audition are compatible with the idea that retro-cues enhanced the memory trace of a sound that was already perceived, and are thus interpreted as postperceptual effects of the retro-cue on memory consolidation (see the "Discussion" for a further review of this literature). This is in line with the idea of a tight link between attention and working memory (Cowan, 1999; Oberauer, 2002, 2009) but says little about the role of retro-cueing for conscious access (C. Koch & Tsuchiya, 2007; Dehaene & Changeux, 2011).

The critical novelty of the present study is to directly test if retro-cueing can also affect whether an auditory stimulus enters conscious awareness or not. As in the visual modality, the originality of our approach relies on two aspects: first, we used a protocol that is known to directly affect conscious awareness of auditory stimuli (dichotic listening), while trying to keep memory load low; second, we directly probed conscious awareness of our stimuli of interest by complementing objective performance measures with a subjective audibility scale, as is routinely done in studies of visual conscious perception (Del Cul et al., 2007; Overgaard & Sandberg, 2021; Sergent & Dehaene, 2004a; Sergent et al., 2005, 2013, 2021). We designed a dual-task in a two ears (dichotic) speech presentation paradigm (Broadbent, 1952). Different streams of words were presented to the left and right ear. Participants had to perform a speeded categorization task in one ear, which was designated as the primary task. The categorization consisted in responding to animal names and not responding to distractor words (nonanimal). In addition, a secondary task was introduced, for which participants had to report at the end of the trial the identity of a target stimulus, which could appear at random times during the trial in the opposite ear to the primary task. The target stimulus was the only word in the secondary stream, embedded in a stream of nonwords, and it was the name of one of three possible geometric figures ("square," "circle," or "triangle"). On some trials, a visual cue instructed participants to temporarily orient their attention to the secondary task. Importantly, this cue was displayed either *before* (pre-cue) or *after* (retro-cue) the target word. The experiment was designed and piloted so as to yield threshold performance in the absence of cueing (the target is missed on approximately half of the trials) to optimize our sensitivity to potential cueing effects. Pre-cues were predicted to improve objective performance and perceptual sensitivity, as previously demonstrated (Asbjørnsen & Hugdahl, 1995; Mondor & Amirault, 1998; Mondor & Breau, 1999; Mondor & Zatorre, 1995). However, the precise effect of retro-cues on both objective performance and subjective audibility was unknown.

Experiment 1 tested the effect of retro-cueing on objective performance. Experiment 2 tested both objective performance and subjective report. In both experiments, we analyzed the interaction between the effect of cueing and response delay on performance in order to assess the contribution of memory processes (Chan & Alain, 2019, 2021; Lim et al., 2015) previously invoked as underlying the retro-cue effect (Souza & Oberauer, 2016). In Experiment 2, an additional model was fitted to the audibility data to test whether the cue globally increased audibility, or whether it specifically changed the balance between "not heard" and "fully heard" trials (Sergent, 2018; Sergent et al., 2013). As will now be described, our results reveal an as-yet unknown temporal flexibility of conscious auditory perception relative to sound presentation.

Experiment 1

Participants

The sample size of these two experiments was selected based on a power analysis using the effect size of retro-cues observed in a pilot study including 20 participants (using the function sampsizepwr for *t*-tests, Matlab). The design and results of this pilot study are reported in the online supplemental materials. Twenty-one participants were estimated necessary to reach a power of 0.9 and were recruited for this first experiment (11 women, ranging from 21 to 38 years old, $M = 26$ years old). All participants were right-handed and reported normal or corrected-to-normal vision and no hearing impairment. All were native French speakers. The study was validated by the ethics committee of Paris Descartes (CERES). Participants all gave informed written consent beforehand. They received a compensation of 10€/hr.

Material and Stimuli

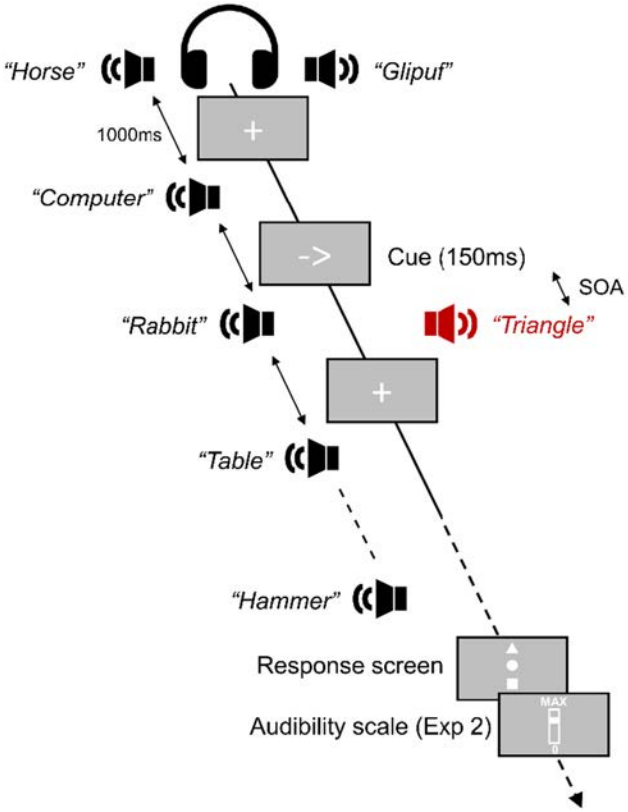
The sound set for the primary categorization task consisted of 149 target words (to which participants had to respond by pressing a button), which were names of animals with a length of 1–4 syllables; 346 distractor words (to which participants were instructed not to respond to), which were other words unrelated to animals, also with a length of 1–4 syllables. The sound set for the secondary task consisted of 100 pseudowords, which were manually generated with a length of 2–3 syllables; three target words, which were French names of geometrical shapes with a length of 2–3 syllables: "cercle," "carré," and "triangle" ("circle," "square," and "triangle," respectively). All sounds were recorded in French with a Bird UM1 microphone. The target and distractor stimuli used for the primary task were recorded with a male voice, while the targets and pseudowords used for the secondary task were recorded with a female voice. All sounds were first normalized using Praat software (Boersma, 2001), setting stimuli used in the primary task to be 25 dB louder than sounds for the secondary task. These differences in speaker and sound intensity were intended to help participants focus their attention on the primary task (Eich, 1984; Wood et al., 1997). Stimulus onset and duration was determined using an aligning tool within Praat (EasyAlign): primary and secondary tasks stimuli lasted, on average, 624 and 520 ms, respectively. Auditory stimuli were presented through headphones (Sennheiser HD 429) using the ASIO4ALL driver. Sampling rate was 44.1 kHz at 16 bits encoding. Sound intensity was calibrated (miniDSP EARS) to be 66 dB SPL A-weighted for the primary task.

The visual cue was a white arrow subtending 2° of visual angle which was displayed for 150 ms at the center of the screen and pointed to the right, which was always the side of the secondary task (see below for motivation of this choice). The background screen remained gray during the whole duration of the experiment, with a white cross in the center of the screen used as a fixation point during the trials. A 22″ cathode-ray tube screen (Diamond Pro 2070SB) was used for displaying the visual stimuli. Audio-visual delay was measured using a photodiode and oscilloscope and compensated for in the stimulus-onset asynchronies (SOAs) computation. The experiment was implemented with the Psychtoolbox in Matlab (2015b). Data and Matlab scripts used for experimental procedure and analysis are available at the following link: https://osf.io/ukhct/?view_only=3c85be6a5a1a49cd86c0beb1751cb90b.

Procedure

The procedure is illustrated in Figure 1. During each trial, 10 words were presented to the participant's left ear, at a constant pace (1 word per second). Concurrently, five stimuli were presented to the right ear (four pseudowords and a target word) at a rate of one

Figure 1
General Experimental Protocol



Note. For each trial, 10 stimuli were played in the left ear, for the primary task and five in the right ear, for the secondary task. A visual cue (arrow) could replace the fixation cross either before (pre-cue) or after target presentation (retro-cue). Experiment 2 included an audibility scale for the participant to report the subjective quality of their perception of the target stimulus. Headphone icon from IconScout by Phoenix Dungeon (iconscout.com/). See the online article for the color version of this figure.

stimulus every 2 s. The primary ear was always the left ear and the secondary ear was always the right ear, since we wanted to leverage the so-called right-ear advantage (Aydelott et al., 2012; Kimura, 1961) to maximize the chance of the secondary target to be processed to some extent.

Participants were instructed to perform a dual task. The primary task consisted of a categorization task on the words played to their left ear. They were instructed to press the space bar of a computer keyboard as fast as possible when they heard the name of an animal (primary targets), and refrain to press any key for any other word (primary distractors). A random number of primary targets (2–5) were included in each trial. To focus attention toward the primary stream, the experimenter explicitly designated this task as the main one and stressed the importance to respond both quickly and accurately. Participants were warned that the button press had to occur before the next word was played in order to be correctly registered. In practice, as the interval between sound onsets was short (1 s), a response was associated with a word if it occurred between 0.25 and 1.25 s after the onset of that word. Feedback on performance at the primary task was provided at the end of each block.

The secondary task consisted in detecting and recognizing a secondary target word (henceforth, secondary target) among pseudowords in the right ear. On each trial, a set of five stimuli was played in the secondary ear at a constant pace starting simultaneously with the first or second word of the primary ear, at random. Participants were instructed that one of three possible secondary target words, "triangle," "square," or "circle" ("triangle," "carré," or "cercle" in French), was presented to the secondary ear, and that they had to report it at the end of the trial. They were informed that only one of them appeared in the secondary ear for each trial. The secondary targets appeared at a random position within the sequence, from 3 to 8 with respect to the onset of the primary speech stream, yielding six possible delays between the secondary target and the response screen, from 3 to 8 s.

A visual cue, displayed for 150 ms in the center of the screen, was included in 75% of the trials. In response to this cue, participants were instructed to temporarily switch to the secondary task, namely to reorient their attention to the right ear in order to identify the secondary target that could have been presented around the time of the cue. In Experiment 1, the cue was always informative of the presence of a secondary target. However, the cue could be presented at three possible SOAs relative to the secondary target: −500 ms (pre-cue), 1,000 ms (early retro-cue) and 1,500 ms (late retro-cue). Since the mean duration of the secondary target was 480 ms and the cue displayed for 150 ms, this resulted in average interstimulus interval of −350, 520, and 1,020 ms, respectively.

At the end of each trial, a response screen appeared displaying three geometric shapes (a triangle, a square, and a circle). Participants were asked to select the geometric shape corresponding to the secondary target they heard using the keyboard. This secondary task was designed as a forced-choice paradigm: participants were instructed to select one of the three propositions even when they thought they did not hear any secondary target.

Participants performed a training session of 24 trials, followed by 288 experimental trials split into six blocks for the experiment, yielding 72 trials per cueing condition (and 12 trials per cueing condition at each possible secondary target position within the sequence). At the end of each block, the participants could take a small break and received feedback on their performance at the primary task.

Results

Overall Performance

Overall, participants performed both the primary categorization task and the secondary identification task with good accuracy. The mean categorization accuracy on the primary task was 84.85% correct ($SD = 4.17$); mean identification accuracy on the secondary task was 77.16% correct ($SD = 14.68$). In particular, the mean identification accuracy on the secondary task in the absence of a cue was 70.97% correct ($SD = 16.86$). As intended and as calibrated in the pilot study (see the online supplemental materials), this level of performance in the control "no cue" condition is close to threshold performance (halfway between the chance level of 33% correct and perfect performance of 100% correct), and hence, is well above chance—comparison with chance level: $t(20) = 10.23$, $p < .001$, $d = 2.52$, 95% CI [63.29, 78.64]. It is important to note that we did not intend the secondary target to be always inaudible for this baseline "no cue" condition, as floor effects may have confounded interpretation of the putative effects of cueing. Rather, we intended the secondary target to be around the threshold, so it would be missed on approximately half of the trials to optimize sensitivity to cueing.

Primary Task

The categorization accuracy on the primary task showed that participants complied with the instructions. It can also be further analyzed to test whether the cue was effective in initiating an attentional shift toward the secondary stream. To do so, we computed categorization sensitivity (or d') for the primary stimuli around secondary target and cue presentation. If the cue indeed reoriented attention toward the secondary task, sensitivity for the primary task should decrease following cue onset as less resources would be available for this task. We performed our analysis on an interval ranging from three primary stimuli before the secondary target (-3) to three primary stimuli following it (+3). A larger analysis interval could not be used as the secondary target position ranged from 3 to 8 out of 10 primary stimuli, so even the -3 and +3 intervals have less data than other intervals. Figure 2A shows the categorization sensitivity (d') on a primary stimulus as a function of its position relative to the secondary target and to the reorienting cue. Relatively to the "no-cue" condition, both pre- and retro-cues seemed to decrease the d' values for primary stimuli presented at the same time or just after the cue. We confirmed these observations using a repeated measures analysis of variance (ANOVA) on categorization sensitivity for the primary task, with two within-participant factors: cueing (four levels: no cue, pre-cue, early retro-cue, late retro-cue) and the relative position of the primary stimulus regarding the onset of the secondary target (seven levels: from -3 to +3 by steps of 1, each step corresponding to a 1 s SOA). We observed significant main effects of cueing condition, $F(2.90, 57.98) = 4.36$, $p = .008$, $\eta_p^2 = 0.18$, Greenhouse–Geiser correction applied to account for violation of sphericity, and serial position, $F(3.21, 64.13) = 47.24$, $p < .001$, $\eta_p^2 = 0.70$, Greenhouse–Geiser correction used. Importantly, the interaction between the two factors was also significant, $F(8.72, 174.48) = 9.75$, $p < .001$, $\eta_p^2 = 0.33$, suggesting that cueing did affect detection sensitivity of the primary stimulus, but that this effect depended on the timing of the cue relative to the primary stimulus.

To further investigate the timing of these effects, we compared the three cueing conditions to the no-cue condition at the different positions in the sequence. We used post hoc paired *t*-tests, with a Bonferroni correction for multiple comparisons (21 comparisons). These comparisons did not show any significant difference in categorization sensitivity for primary stimuli preceding the secondary target (all *p*-corrected > .05). This was expected since no cue was displayed concurrently to these primary stimuli. Importantly, paired comparisons showed a decrease of sensitivity for the primary stimuli that were presented immediately after the cue in the pre-cue condition, hence simultaneously with the secondary target, $t(20) = 7.03$, *p*-corrected < .001, $d = 1.53$, 95% CI [0.76, 1.40]. For early retro-cues, which were presented 1 s after the secondary target, and thus concurrently with a primary stimulus, we observed a significant decrease in sensitivity both for this primary stimulus and the next one: $t(20) = 4.75$, *p*-corrected = .003, $d = 1.04$, 95% CI [0.29, 0.74] and $t(20) = 3.58$, *p*-corrected = .039, $d = 0.78$, [0.24, 0.90], respectively. Finally, for late retro-cues, which were presented 1.5 s after the secondary target, that is, in between two primary stimuli, we observed a significant decrease in sensitivity for the primary stimulus immediately following the cue, $t(20) = 5.03$, *p*-corrected = .001, $d = 1.10$, 95% CI [0.40, 0.96]. No other comparison yielded any significant difference (all *p*-corrected > .05). This pattern of results is exactly what is expected if the cue induces a temporary switch from the primary task to the secondary task.

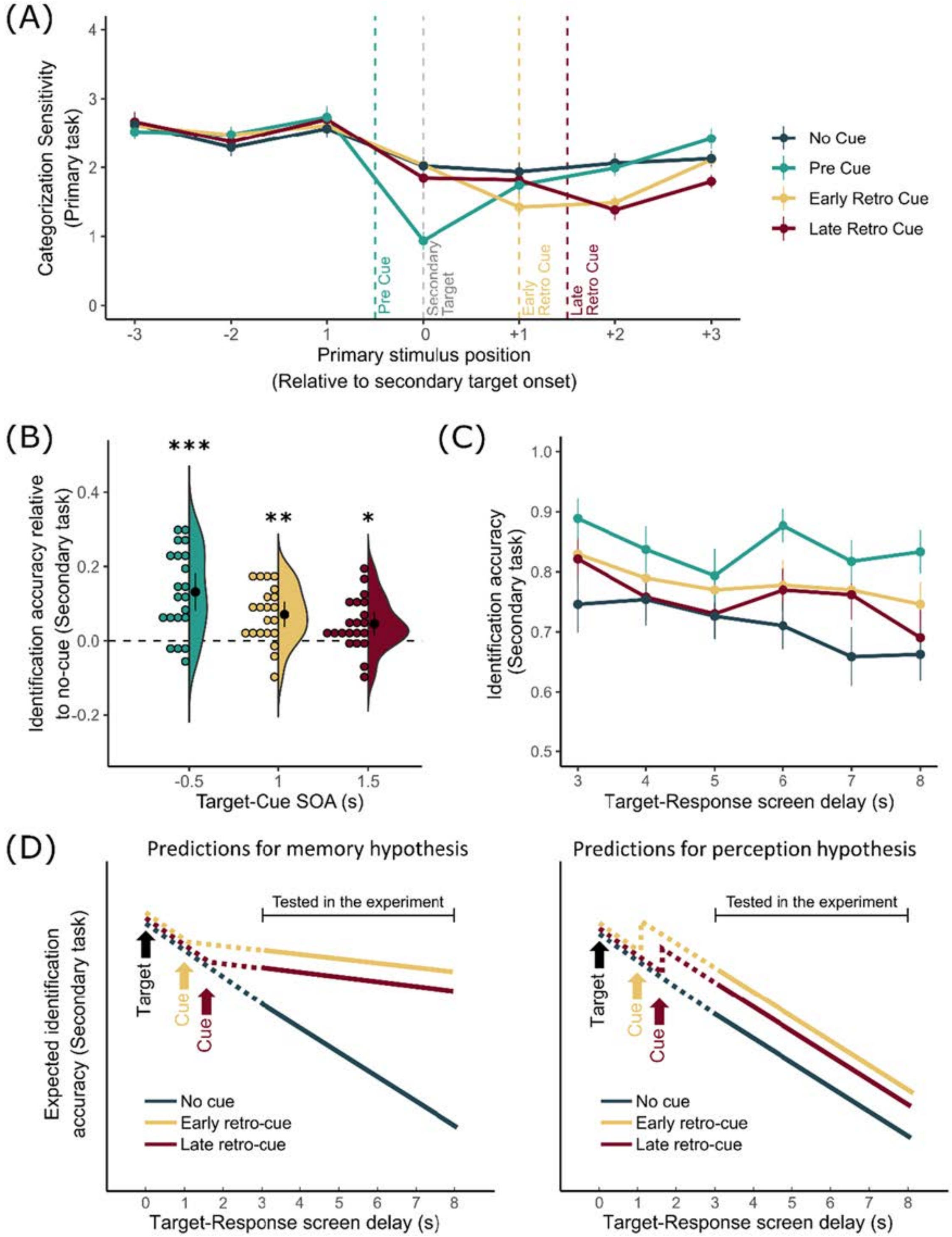
Following suggestions for post hoc analyses, we conducted a similar approach on mean correct response times (RTs) on the primary task, expecting an increase of RTs following the cue. However, because the primary categorization task required a response only for a fraction of the stimuli, this analysis could not be conducted with all participants. Four of them were excluded due to a lack of correct detection for at least one of the serial positions. The ANOVA only yielded a significant main effect of serial position, $F(3.76, 60.22) = 8.09$, $p < .001$, $\eta_p^2 = 0.34$, Greenhouse–Geiser correction applied to account for violation of sphericity, while both the main effect of the cueing condition, $F(2.31, 37.00) = 0.40$, $p = .705$, $\eta_p^2 = 0.02$, Greenhouse–Geiser correction used, and the interaction between the two factors, $F(4.30, 68.80) = 1.15$, $p = .342$, $\eta_p^2 = 0.07$, remained below the significance threshold (see Figure S2A in the online supplemental materials).

Finally, we investigated the effect of primary task demand on secondary task performance. More specifically, we tested if the need to provide a motor response to a primary stimulus (primary target, i.e., when the word designated an animal) had an effect on secondary task accuracy (see Figure S3 in the online supplemental materials). A 2 × 4 ANOVA with the type of primary stimulus (two levels: primary target—hence a response is required, primary distractor—hence no response is required) and the cueing condition (four levels: no cue, pre-cue, early retro-cue, late retro-cue) as within subjects' factors was performed separately for primary stimuli that were presented just before or simultaneously with the secondary target. This analysis revealed a main effect of the type of primary stimulus presented *before* the secondary target, $F(1, 20) = 11.33$, $p = .003$. When the primary stimulus preceding the secondary target required a response, participants performed significantly worse at the secondary task, $t(20) = 3.45$, $p = .003$, 95% CI [1.94, 7.86], than when no response was required (see Figure S3A in the online supplemental materials). This effect interacted with the cueing condition, $F(2.38, 47.56) = 3.34$, $p = .036$, with post hoc *t*-tests showing that the effect was present in the no cue, $t(20) = 3.26$, *p*-corrected = .016, $d = 0.71$, 95% CI [3.52, 16.00], and pre-cue conditions only, $t(20) = 2.83$, *p*-corrected = .042, $d = 0.62$, [1.57, 10.42]. In contrast, for the primary stimuli that were played *simultaneously* with the secondary target, we did not find a significant main effect of the type of primary stimulus, $F(1, 20) = 1.09$, $p = .308$.

To summarize, when a cue was displayed, a significant decrease in categorization sensitivity selectively appeared for the first one or two primary stimuli following its onset. Reciprocally, secondary task identification accuracy was modulated by the need to provide a response to the primary stimulus preceding the secondary target presentation. This pattern of results is fully consistent with a transient attentional reorientation toward the secondary stream initiated by the visual cue (Wood & Cowan, 1995). The lack of effect on RTs on the other hand may be due to a lack of statistical power. Indeed, in this primary task participants only produce a response for a fraction of the stimuli. As the sensitivity decreased, the correct detections were also fewer, leaving a scarce number of responses to compute RTs over the different serial positions.

Figure 2

Effect of Retrospective Attention on Word Identification Performance—Experiment 1



(A) Categorization sensitivity at the primary task as a function of the primary stimulus serial position relative to the onset of the secondary target in the different cueing conditions. (B) Cueing effect (difference between cued and noncued trials) on the identification accuracy of the secondary target in the different cueing conditions (secondary task). (C) Evolution of secondary target identification accuracy according to the delay between secondary target onset and response screen in the different cueing conditions. (D) Schematic representation of the memory-based and perceptual hypotheses' predictions on secondary target identification accuracy as a function of the cueing condition and the delay between the secondary target and the response screen. Error bars represent the standard error of the mean in all plots. See the online article for the color version of this figure.

Secondary Task: Identification of the Target Word

We now address our central question by assessing the effect of the cue on the proportion of correct target identification in the secondary task. A repeated measures ANOVA revealed a main effect of cueing (four levels: no-cue, pre-cue, early retro-cue, late retro-cue) on identification accuracy, $F(1.99, 39.87) = 20.01$, $p < .001$, $\eta_p^2 = 0.50$. To characterize this main effect of cueing, we compared each cueing condition with the nocue condition. These comparisons are shown in Figure 2B, where the identification accuracy without cueing was subtracted from each cued condition for each participant. Bonferroni-corrected comparisons (three comparisons) showed that precueing significantly improved accuracy, SOA $= -500$ ms, $t(20) = 5.38$, p-corrected $< .001$, $d = 1.17$, 95% CI [8.06, 18.26]. Crucially, this was also the case for early retro-cueing, SOA $=$ 1,000 ms, $t(20) = 4.31$, p-corrected $= .001$, $d = 0.94$, 95% CI [3.65, 10.50], and late retro-cueing, SOA $=$ 1,500 ms, $t(20) =$ 2.94, p-corrected $= .024$, $d = 0.64$, [1.33, 7.80]. Therefore, cueing improved identification accuracy at all SOAs, including for retro-cues.

A post hoc analysis revealed a main effect of the identity of the secondary target on accuracy, $F(1.99, 39.87) = 20.01$, $p < .001$, $\eta_p^2 = 0.50$, Greenhouse–Geiser correction used, with "Circle" being correctly reported more often, $M = 84.08$, $SD = 14.05$, than "Square," $M = 74.26$, $SD = 16.50$, and "Triangle," $M = 73.16$, $SD = 17.10$. This suggests that one secondary target was slightly easier to identify in this dual-task paradigm. There was no significant interaction between the identity of the secondary target and the cueing condition, $F(4.46, 89.12) = 2.28$, $p = .060$, Greenhouse–Geiser correction used. In addition, all targets appeared in the same number of trials in all cueing conditions.

Secondary Task: Disentangling Perceptual Versus Memory Interpretations of the Retro-Cueing Effect

To summarize the results so far, a positive effect of attentional cueing was found on the identification of an auditory target word, both when the cue appeared before and after the secondary target. Moreover, the primary task performance decreased momentarily after the visual cue, suggesting that it was efficient in inducing an attentional shift (Wood & Cowan, 1995).

These results could be consistent with two fundamentally different interpretations. First, this pattern of results would be consistent with our hypothesis that attentional reorientation induced retrospective conscious access. But another possible interpretation would be that retro-cueing acted on the consolidation in memory of already conscious information, rather than on conscious access per se, as previously shown (Griffin & Nobre, 2003). Specifically, an interpretation of our results in terms of memory (Souza & Oberauer, 2016) would state that reorientation of attention did not increase the perception of the targets, but rather prevented already-conscious targets from being forgotten before the response had to be provided. As the memory load is minimal here (only one item to maintain), the effect of the cue would then essentially consist in counteracting perceptual interferences and temporal decay of the stimulus representation in working memory.

These two competing interpretations were tested by analyzing the details of performance over time for the secondary task. Figure 2C shows identification accuracy at the secondary task as a function of the delay between the secondary target and the response screen, in the different cueing conditions. As both perceptual interferences and memory decay should increase with delay, the "memory hypothesis" predicts that retro-cueing should essentially change the slope of the forgetting curve occurring between the secondary target presentation and the delayed response screen, leading to an interaction between the cueing condition and the target–response delay (illustrated in Figure 2D, left). Alternatively, if the retro-cue increased the chance that the secondary targets were consciously heard, and hence entered working memory, this should result in an overall increase in accuracy, with no change in the slope of the curve (illustrated in Figure 2D, right). In this case, we should observe no interaction between cueing conditions and target–response delay.

We thus tested whether our results were consistent with the presence or absence of such interaction. This required conducting a Bayesian repeated measures ANOVA, since a frequentist analysis does not allow estimating symmetrically the evidence in favor of either the presence or absence of an effect. We compared five models: two models that assumed that either cueing or delay affected performance, but not both; one that assumed that both factors influenced performance but with no interaction; one that assumed that both factors influenced performance with interaction; and finally, a null model with no effect of either factor. All models were set to the same prior probability, $P(M) = 0.2$, before analysis. The results of this analysis conducted using Jeffreys's Amazing Statistics Program (https://jasp-stats.org/) are shown in Table 1. The model postulating a main effect of both factors with no interaction (reflecting the "perception" hypothesis) was found to be the most likely by far, $P(M|\text{data}) = .986$. The model including the interaction (reflecting the "memory" hypothesis) was much less probable, $P(M|\text{data}) = .013$, as reflected by the corresponding Bayes factor ($BF_{01} = 73.59$). In other words, the model including the interaction between cue and delay as a predictor was found nearly 74 times less likely than the model without it.

This analysis thus strongly suggests an absence of interaction between cueing and delay, and therefore is inconsistent with the memory interpretation positing that retro-cueing prevents consciously-heard items from decaying in working memory. Rather, it is consistent with the hypothesis that the retro-cue retrospectively triggered conscious access to the secondary target, independently of the delay between the target and response.

Experiment 2

In this next experiment, we aimed to provide a more direct test of the interpretation of retro-cueing in terms of perceptual awareness. There is extensive literature discussing the most appropriate way to collect direct measures of conscious awareness (reviewed in the "Discussion"). Here, we used two complementary secondary tasks on each trial: an identification forced-choice task, identical to Experiment 1, and a rating of subjective audibility ranging on a scale from "not heard at all" to "perfectly heard." These data were used to derive three complementary measures of conscious perception: the identification task was used to derive identification accuracy, and the subjective task was used to derive detection sensitivity (d') and subjective audibility. In order to estimate d', we needed to introduce catch trials, namely, trials in which the secondary stream contained no target. These catch trials were introduced on 25% of all trials. Our predictions were that, if the

Table 1

Bayesian Repeated Measures ANOVA for Experiment 1

Models	$P(M)$	$P(M\|\text{data})$	BF_M	BF_{01}	Error (%)
Model comparison					
Cue + Delay	0.20	0.986	278.83	1.00	
Cue + Delay + Cue × Delay	0.20	0.013	0.05	73.59	1.21
Cue	0.20	7.452e−4	0.00	1,323.00	2.44
Delay	0.20	2.655e−15	1.062e−14	3.714e+14	1.02
Null model (incl. participant)	0.20	1.597e−17	6.388e−17	6.173e+16	0.91

Note. All models include participants. The "Models" column reports the predictors used for each model. The prior $P(M)$ and posterior $P(M|\text{data})$ probabilities for each model are reported in corresponding columns. BF_M shows the change from prior to posterior odds for each model. BF_{01} corresponds to the Bayes factors of the best model over each other model (how many times more probable is the best model compared to this one). Models are ranked from the most to the less likely considering the data. ANOVA = analysis of variance.

retro-cue induced a retro-perception effect, we should observe an increase not only in identification accuracy but also in detection sensitivity and audibility compared to the no cue condition. Moreover, and importantly, if cueing induces conscious perception of the secondary target on trials where it would not have been heard otherwise, audibility should increase because of an increase of the proportion of high-audibility versus no-audibility trials, and not as a gradual shift of audibility throughout the audibility scale.

Participants

Twenty-one participants (14 women, ranging from 19 to 38 years old, $M = 26$ years old), were recruited for Experiment 2, based on the same power analysis as Experiment 1. None had taken part in Experiment 1. All were right-handed and reported normal hearing and normal or corrected-to-normal vision. The study was validated by CERES. Participants all gave informed written consent before the experiment. They received a compensation of 10€/hr for their participation.

Material and Stimuli

All the devices and stimuli used for this second experiment were the same as in the first experiment.

Procedure

The paradigm used in Experiment 2 was similar to the one used in Experiment 1. As in Experiment 1, trials were sequences of auditory stimuli presented dichotically (10 in the left ear, five in the right one). Participants were asked to perform a speeded primary, categorization task in the left ear and to perform a secondary identification task on stimuli presented to the right ear, consisting of reporting, at the end of the trial, the identity of a target word presented in that ear. In addition, a subjective audibility rating of the secondary target was demanded after the identity question on each trial. Catch trials were also included, where the secondary target was replaced by a pseudoword. These catch trials represented 25% of the 384 trials completed by each participant. They were associated with a cue in the same proportion (75%) as the target present trials. Therefore, the presence of a cue was not predictive of the presence or absence of a target: the probability that a target was present was the same on cued and not cued trials, 75% in both cases.

Participants had to report one of the three possible secondary targets at the end of the trial, even when none was presented. They were informed of the existence of catch trials and instructed to select randomly one of the three possible responses if they did not hear a secondary target stimulus. Identification accuracy was subsequently computed on trials including a secondary target only. After participants had performed this forced choice identification task, audibility ratings were collected. A vertical 11-point audibility scale was displayed at the center of the screen. Participants were instructed to move a cursor according to the subjective audibility of the putative secondary target using the keyboard (Sergent & Dehaene, 2004a; Sergent et al., 2005, 2021). If they did not hear any secondary target, they were told to place the cursor at the lowest end of the scale (labeled "0"). Participants were asked to use the lower half of the scale if they perceived a target but found it barely audible and the upper half of the scale if it was audible. If the target was perfectly clear, participants were told to use the highest point of the scale (labeled "Max"). Participants were encouraged to use the entire scale to report as precisely as possible the subjective quality of their perception (full instructions in the online supplemental materials).

Results

Overall Performance

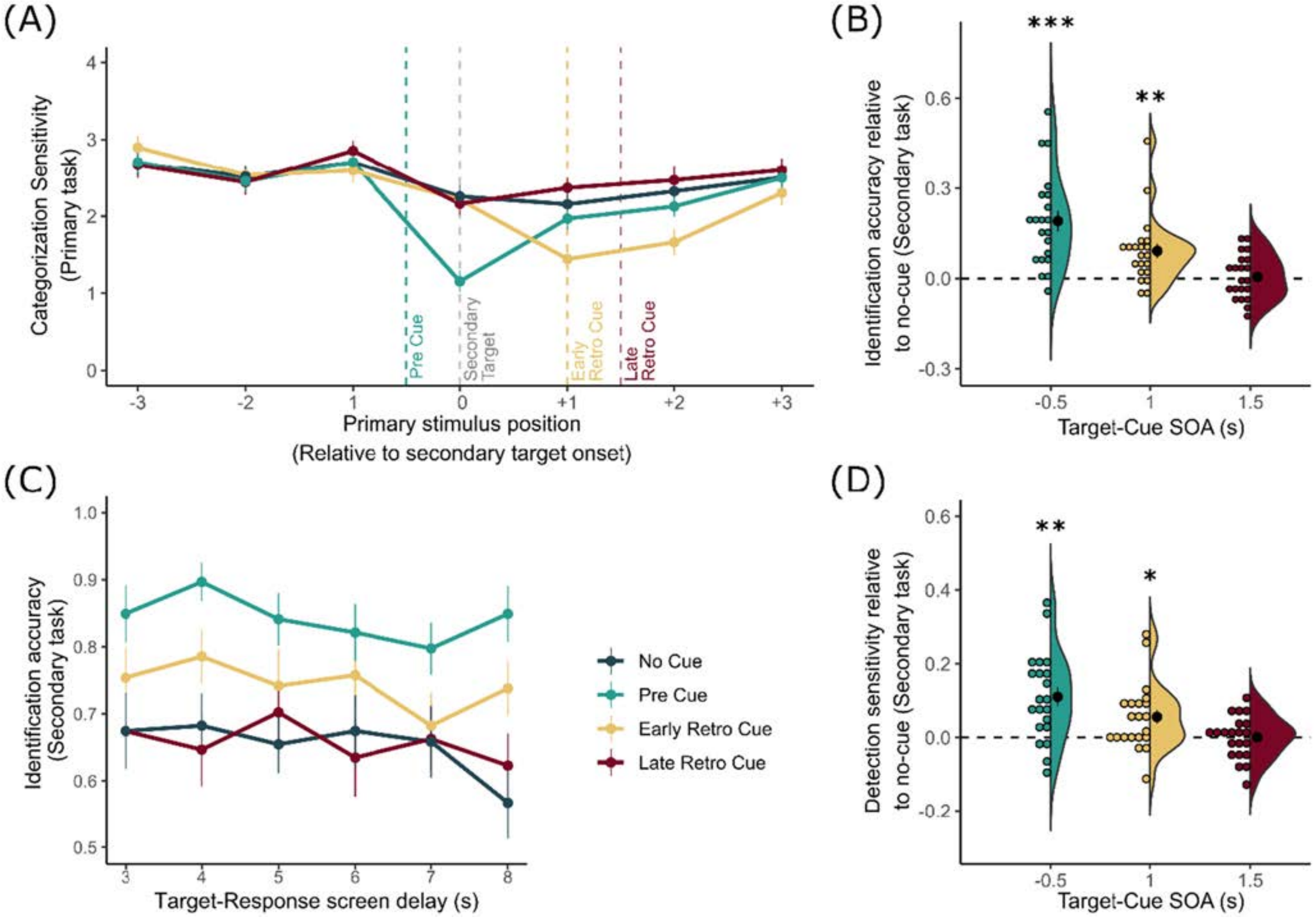
As for Experiment 1, participants performed both the primary categorization task and the secondary identification task with good levels of accuracy across all cueing conditions (primary task: $M = 86.69\%$, $SD = 4.85$; secondary task: $M = 72.39\%$, $SD = 17.61$). Identification accuracy on the secondary task in the absence of a cue (control condition) was again, as intended, around threshold accuracy of 66% ($M = 65.21\%$, $SD = 21.46$) and significantly higher than chance, comparison with accuracy of 33%, $t(20) = 6.81$, $p < .001$, $d = 2.00$, 95% CI [55.45, 74.98], to prevent floor or ceiling effects.

Primary Task

As for Experiment 1, we first checked that the effect of cueing was compatible with switching of attention to the secondary task. The categorization sensitivity for the primary task as a function of the relative positions of the secondary target and cue is shown in Figure 3A. A repeated measures ANOVA was performed on

Figure 3

Effect of Retrospective Attention on Word Identification and Detection—Experiment 2



(A) Error rate on the primary detection task as a function of the primary stimulus serial position relative to target onset and cueing condition. (B) Cueing effect, defined as the difference between cued and no cued trials on identification accuracies in the secondary task, as a function of the cueing condition. The horizontal dashed line indicates no effect of cueing. (C) Target identification accuracy in the secondary task as a function of the delay between target onset and response screen in the different cueing conditions. (D) Cueing effect on detection sensitivity as a function of the different cueing conditions. See the online article for the color version of this figure.

categorization sensitivity, with factors of cueing (four levels: no cue, pre-cue, early retro-cue, and late retro-cue) and position of the primary stimulus relative to the secondary target played on the opposite ear (seven levels). Again, both main effects of cueing, $F(2.76, 55.12) = 17.65$, $p < .001$, $\eta_p^2 = 0.47$, Greenhouse–Geiser correction applied, and position, $F(3.42, 68.34) = 28.97$, $p < .001$, $\eta_p^2 = 0.59$, were significant, as well as the interaction between the two, $F(8.52, 170.48) = 10.50$, $p < .001$, $\eta_p^2 = 0.34$. Post hoc comparisons between the pre-cue and the no-cue conditions showed an decrease in primary categorization sensitivity on the stimulus immediately following the cue: simultaneous with secondary target presentation, $t(20) = 7.09$, p-corrected $< .001$, $d = 1.55$, 95% CI [0.78, 1.43]. A similar decrease was obtained for early retro-cues, for the primary stimulus played at the same time as the cue, $t(20) = 6.73$, p-corrected $< .001$, $d = 1.47$, 95% CI [0.49, 0.93], and the following stimulus, $t(20) = 4.88$, p-corrected $= .002$, $d = 1.06$, 95% CI [0.38, 0.95]. In contrast, we observed no such decrease in primary categorization sensitivity following cue onset for late retro-cues.

As for Experiment 1, we replicated the analysis on response times. In Experiment 2, most participants could be included in the analysis as a mean response time could be computed on all serial positions for 20 out of the 21 of them. However, we obtained similar results to those of the first experiment, with the ANOVA yielding a significant main effect of serial position, $F(2.14, 40.64) = 5.82$, $p = .005$, $\eta_p^2 = 0.23$, Greenhouse–Geiser correction applied to account for violation of sphericity, but not of the cueing condition, $F(1.53, 29.14) = 1.66$, $p = .210$, $\eta_p^2 = 0.08$, Greenhouse Geiser correction used, nor the interaction between the two factors, $F(2.33, 44.27) = 1.32$, $p = .279$, $\eta_p^2 = 0.06$, see Figure S2B in the online supplemental materials.

We also reproduced the analysis investigating the effect of primary task demand on identification accuracy in the secondary task (see Figure S3B in the online supplemental materials). As in Experiment 1, we found a significant main effect of the type of primary stimulus preceding the secondary target, $F(1, 20) = 8.71$, $p = .008$, $\eta_p^2 = 0.30$, with a decrease in secondary identification performance when a response was required on the primary stimulus,

$t(20) = 3.30$, $p = .004$, 95% CI [1.30, 5.78]. However, this effect did not interact with the cueing condition, $F(2.54, 50.87) = 0.27$, $p = .81$, Greenhouse–Geiser corrected. Finally, as in Experiment 1, no such effect was observed for the primary stimulus played simultaneously with the secondary target, $F(1, 20) = 0.07$, $p = .792$.

In summary, this pattern of results is fully consistent with a reorienting of attention following the cue, for pre-cues and early retro-cues, but not late retro-cues.

Secondary Task: Identification of the Target Word

We next tested whether identification accuracy at the secondary task was improved by the cue. As for Experiment 1, a repeated measures ANOVA (four levels: no-cue, pre-cue, early and late retro-cue) revealed a main effect of cueing on identification accuracy, $F(1.81, 36.19) = 20.62$, $p < .001$, $\eta_p^2 = 0.51$, Greenhouse–Geiser corrected. To characterize this main effect of cueing, we compared each cueing condition with the no-cue condition independently. The effect of cueing is shown in Figure 3B. Bonferroni-corrected comparisons with the no cue condition showed an increase in identification accuracy for pre-cueing, SOA = −500 ms, $t(20) = 5.57$, p-corrected $< .001$, $d = 1.22$, 95% CI [11.91, 26.18], and early retro-cueing, SOA = 1,000 ms, $t(20) = 3.68$, p-corrected $= .005$, $d = 0.80$, [3.96, 14.30], replicating the effects observed in Experiment 1. Unlike in Experiment 1, we observed no significant increase in identification accuracy for late retro-cues, SOA = 1,500 ms, $t(20) = 0.33$, $p = .748$, $d = 0.07$, 95% CI [−2.86, 3.92].

As in Experiment 1, we found a main effect of the identity of the secondary target on identification accuracy, $F(1.81, 36.19) = 20.62$, $p < .001$, $\eta_p^2 = 0.51$, with "Circle" being correctly reported more often than "Square" or "Triangle" ("Circle": $M = 79.46$, $SD = 19.44$; "Square": $M = 72.52$, $SD = 15.41$; "Triangle": $M = 65.18$, $SD = 22.35$). The interaction between this factor and the cueing condition was not significant, however, $F(4.12, 82.49) = 1.60$, $p = .181$. Finally, looking at catch trials revealed a small bias toward one response ("Square"), selected on average in 36% of the trials against 32% for the two other alternatives, $F(1.74, 34.85) = 5.35$, $p = .012$.

Secondary Task: Disentangling Perceptual Versus Memory Interpretations of Retro-Cueing Effect on Identification

To contrast the perceptual and memory interpretations of the cueing effect, as in Experiment 1, we analyzed how cueing effects interacted with the delay between the secondary target and the response (Figure 3C). We computed a Bayesian repeated measures ANOVA with the same parameters as in Experiment 1 (see Table 2). In this second experiment, the model including only the cueing condition as a factor was found the most probable, $P(M|\text{data}) = .715$, followed by the one including both cue and delay without interaction between them, $P(M|\text{data}) = .273$. Again, the model with an interaction between cueing and delay was found unlikely, $P(M|\text{data}) = .012$. Looking at the Bayes factors, the best model, including only the cue as a predictor, was nearly 62 times more likely than the one including the interaction ($BF_{01} = 61.93$). The comparison of the model including both the cue and delay as predictors to the one with the cue only yielded anecdotal evidence, the former being less than 3 times more likely ($BF_{01} = 2.62$).

As in Experiment 1, the "memory hypothesis" is thus not supported by the data as it would imply a model with both the main effect of the secondary target position and the interaction of this factor with the cueing condition. In contrast, the best model, including the cue as the only factor, is fully compatible with the "perception hypothesis."

Secondary Task: Detection Sensitivity and Audibility Ratings

Conscious access can be defined by the availability of a representation for the subjective report (Block, 1995). To assess the effect of the cue on conscious access to the secondary target, in Experiment 2 participants reported the audibility of this stimulus using a perceptual scale. The audibility ratings obtained for the secondary targets in the different conditions are shown in Figure 4. As instructed, participants used the totality of the scale to rate the audibility of the secondary target. Also, they mainly used the "0" audibility level when no secondary target was actually played, suggesting a correct use of the scale.

To investigate the effect of the cue on these reports, we first computed participants' detection sensitivity based on their ratings on catch trials versus target-present trials. The area under the ROC curve can be estimated from the audibility ratings for target-present and target-absent trials using a signed rank test (Hanley & McNeil, 1982). We performed this computation for each participant to obtain secondary target detection sensitivity in the different cueing conditions. Results are shown in Figure 3D. Compared to the no-cue trials, paired t-tests showed a significant increase in detection sensitivity with pre-cueing, after a Bonferroni correction for

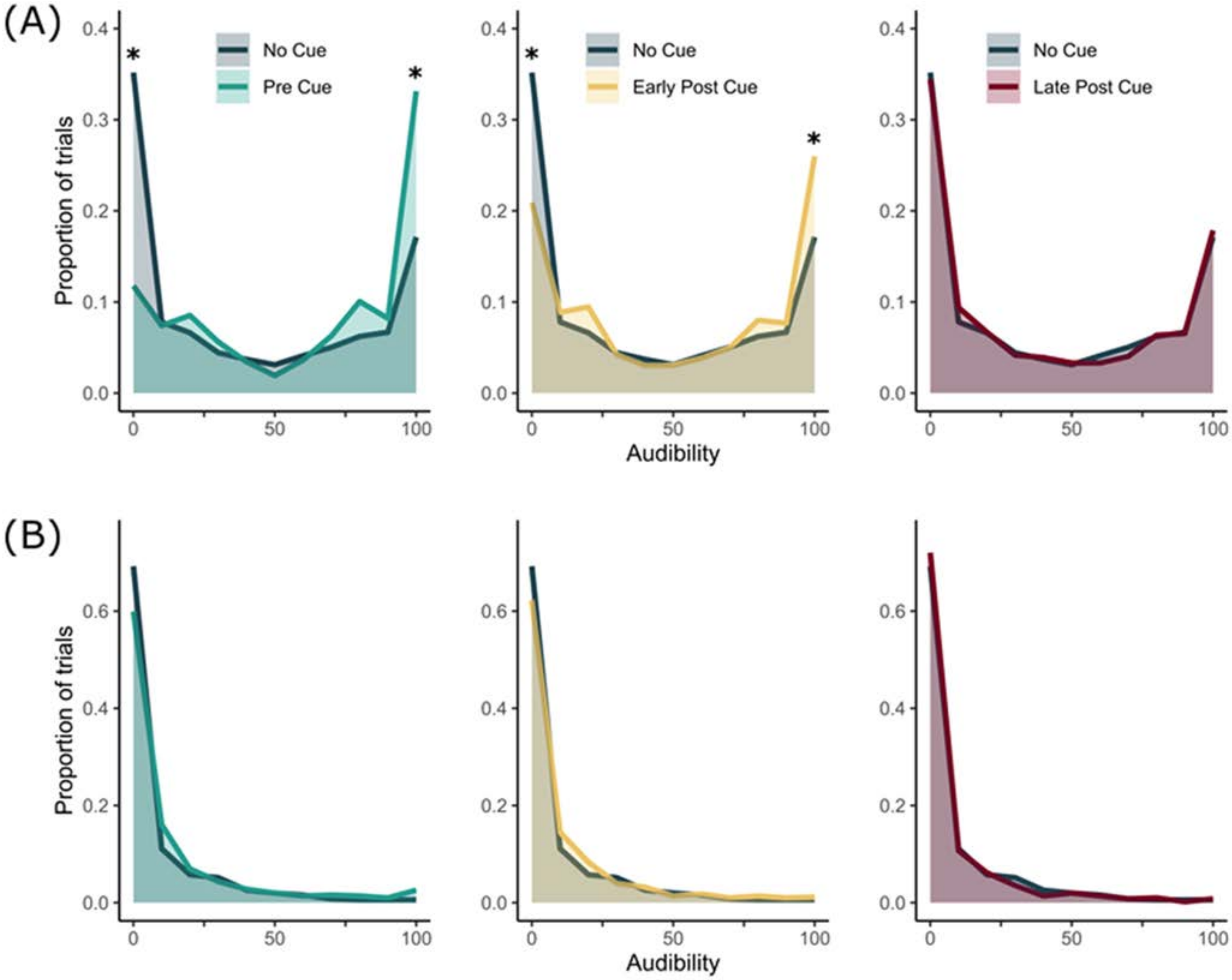
Table 2
Bayesian Repeated Measures ANOVA for Experiment 2

Models	$P(M)$	$P(M\|\text{data})$	BF_M	BF_{01}	Error (%)
Model comparison					
Cue	0.20	0.715	10.05	1.00	
Cue + Delay	0.20	0.273	1.50	2.62	1.23
Cue + Delay + Cue × Delay	0.20	0.012	0.05	61.93	1.38
Null model (incl. participant)	0.20	4.735e−30	1.894e−29	1.511e+29	0.87
Delay	0.20	4.266e−31	1.706e−30	1.677e+30	1.01

Note. All models include participants. The prior $P(M)$ and posterior model ($P(M|\text{data})$) probabilities are reported in corresponding columns. BF_M shows the change from prior to posterior odds for each model. BF_{01} corresponds to the Bayes factors of the best model over each other model (how many times more probable is the best model compared to this one). ANOVA = analysis of variance.

Figure 4

Effect of Retrospective Attention on Subjective Audibility—Experiment 2



Note. The graphs show the distributions of responses on the audibility scale in the different cueing conditions for trials with a target (A) and without a target (B). Stars denote significant differences between the proportion of use of the audibility level in the cued and no-cued trails (**p*-corrected < .05). See the online article for the color version of this figure.

multiple comparisons, *t*(20) = 4.27, *p*-corrected = .001, *d* = 0.93, 95% CI [0.06, 0.16], and early retro-cueing, *t*(20) = 2.82, *p*-corrected = .032, *d* = 0.61, [0.01, 0.10] (Figure 3C). As for identification accuracy, this effect was no longer observed for late retro-cues, *t*(20) = 0.07, *p* = .94, *d* = 0.01, 95% CI [−0.03, 0.03]. Both the pre-cue and the early retro-cue hence increased the objective ability of participants to detect the presence of the secondary target, independently of any potential criterion effects that may have been induced by the cue.

We then analyzed the distribution of subjective audibility ratings (Figure 4). For trials including a secondary target, a clear bimodal distribution of the subjective reports was observed. It is remarkable that the use of opposite audibility ratings on the scale was observed *even though* the strength of the secondary target itself was *strictly identical* in all trials. Importantly, several previous studies have shown that human participants spontaneously use perceptual scales in a gradual fashion when shown with stimuli of various strength (Del Cul et al., 2007; Sergent & Dehaene, 2004a; Sergent et al., 2005, 2013, 2021) confirming that bimodal distributions of responses are not due to poor use of the scale but rather reflect a genuine effect. Crucially, the balance between the two peaks at the two extremes was influenced by the cueing condition. This was tested using paired *t*-tests with False Discovery Rate correction (Benjamini–Hochberg procedure, fdr_bh function on Matlab) which was preferred to Bonferroni's correction because the response rates across the audibility scale are inherently nonindependent. Compared to no-cue trials, the proportion of maximal audibility ratings increased for pre-cued, *t*(20) = 3.50, *p*-corrected = .012, *d* = 0.76, 95% CI [0.06, 0.26], and early retro-cued trials, *t*(20) = 3.04, *p*-corrected = .038, *d* = 0.66, [0.03, 0.15]. This was accompanied by a decrease in the proportion of ratings at zero audibility ratings, *t*(20) = −4.56, *p*-corrected = .002, *d* = −1.00, 95% CI [−0.34,

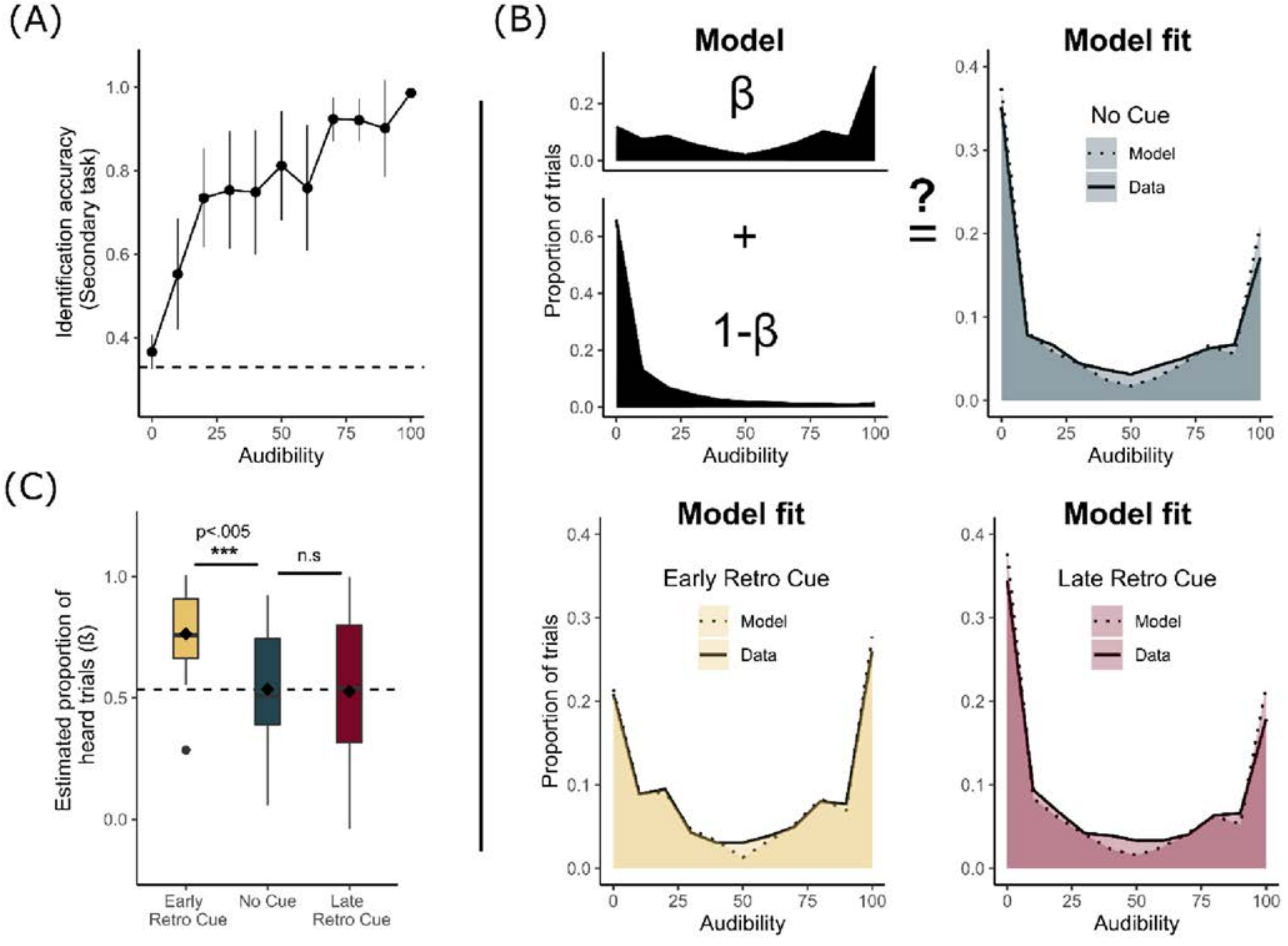
−0.12] and $t(20) = 3.02$, p-corrected = .038, $d = -0.66$, [−0.24, −0.05], respectively. We found no significant differences at all of the other audibility ratings, which we compared across cueing conditions in the same manner. Furthermore, this effect was not due to a response bias induced by the cue since, in catch trials, we found not difference in the distribution of audibility ratings as a function of cueing condition: all distributions were dominated by a clear peak at 0% audibility (Figure 4B).

This first comparison of responses distributions thus suggests that pre and retro-cueing do not induce a gradual increase in the clarity of perception throughout the audibility range, but rather induced a sharp shift in the balance between trials where the stimulus was not heard at all (0% audibility), and trials where it was clearly heard (100% audibility). Again, it is remarkable that these drastic shifts in audibility ratings occurred while the stimuli themselves remained strictly identical. We can further quantify this observation by looking at participants' objective performance at the identification task as a function of how they rated the audibility of the secondary target (Figure 5A): as expected, identification accuracy increased progressively with increasing audibility ratings, and crucially, it started to significantly differ from chance only with the second level of audibility (Figure 5A), confirming that trials where the audibility of the target was rated as zero were veridically trials where participants were unable to report its identity.

The cueing effect on audibility ratings may thus be interpreted as an increase in the number of consciously perceived trials. To explicitly test this account, we modeled the individual audibility distributions in the different cueing conditions as a mixture of two types of distributions (Figure 5B): the distribution observed when the participant could hear the secondary target quite well, for which the "pre-cue" condition is a good template (D_heard) and the distribution observed when the participant did not hear the target at all, for which the "target absent" condition is a good template (D_absent). In this model, each distribution of observed audibility D can then be expressed as $D = \beta \times D\_heard + (1 - \beta) \times D\_absent$, with the β parameter reflecting the proportion of heard trials. Since this

Figure 5

Modeling the Use of the Audibility Scale as a Mixture of Two Distributions of Heard and Unheard Trials



(A) Identification accuracy (secondary task) as a function of reported audibility. (B) Template distributions used for the model (in black) and model fit compared to the actual distribution in the different cueing conditions. All distributions are averages across participants. (C) Estimated proportion of consciously perceived trials (β) in the different cueing conditions. Black diamonds correspond to the average across subjects, box contains data from the 25th to 75th percentiles. The dotted line highlights the average proportion of heard trials at baseline (no cue condition). See the online article for the color version of this figure.

formula is equivalent to D–D_absent = β × (D_heard – D_absent), the β parameter can be estimated by simple linear regression. In practice, this parameter was estimated for each participant separately, with the participant's own templates, so that any idiosyncrasy in the participants' use of the scale could be taken into account (Sergent & Dehaene, 2004a; Sergent et al., 2013).

The model fit was estimated by examining the correlation between the estimated and actual distributions. The model correctly fitted the data for most participants in all conditions: no cue ($M\ r^2 = 0.79$, significant for 20 out of 21 participants); early retro-cue ($M\ r^2 = 0.88$, significant for 20 out of 21 participants); and late retro-cue ($M\ r^2 = 0.78$, significant for 19 out of 21 participants, see the online supplemental materials for the full table of goodness of fits). Figure 5B shows the modeled and observed distributions averaged across participants.

Figure 5C shows the proportion of heard trials estimated by this model (β parameter) in the different cueing conditions. As expected, and as intended, the estimated proportion of heard trials was around 50% for the "no cue" condition. This proportion increased significantly in early retro-cue trials, $t(20) = 3.49$, $p = .002$, $d = 0.76$, 95% CI [0.12, 0.47], reaching 80.27% of heard trials on average, hence an increase of 26.7% compared to no cue trials. In this condition, however, one participant had a parameter value of 2.21. To control that the difference observed was not due to this failure of the model (as the proportion should not be superior to 1), we repeated the comparison excluding this participant. This did not change the pattern of results, but produced a larger estimated increase in the proportion of heard trials in the early retro-cue condition compared to the no-cue condition, $t(19) = 5.13$, $p < .001$, $d = 1.15$, 95% CI [0.13, 0.31]. For late retro-cue, we observed no significant difference with the no cue condition, $t(20) = -0.27$, $p = .790$, $d = -0.06$, 95% CI [−0.08, 0.06]. Note that the regression had to include a constant term, so we checked that this constant term was negligible in all conditions (all values < 1e−16).

This modeling analysis thus fully supports the hypothesis of an increase in the proportion of consciously perceived targets in the early retro-cue condition, at the expense of trials where the secondary target was not consciously accessed at all.

General Discussion

We explored the effect of cueing attention prospectively or retrospectively in a dichotic listening paradigm. Participants performed both a speeded primary categorization task on a speech stream, and a secondary target identification task on another speech stream. Visual cues were used to orient attention to the secondary stream around the time of the secondary target, either before the target (precueing) or after the target (retro-cueing). As expected, pre-cueing improved identification performance, detection sensitivity, and subjective audibility, suggesting a switch of attention to the secondary stream. This effect also occurred for retro-cueing, that is, when the cue was provided *after* the presentation of the secondary target. The retro-cueing benefit was independently observed in two experiments (plus one pilot experiment, see the online supplemental materials), for cues presented up to 1,000 ms after the onset of the secondary target word (i.e., more than 500 ms after its offset); it was observed on two different objective performance measures (identification performance and detection sensitivity) as well as on subjective audibility reports. Finally, we could successfully model the distribution of subjective audibility as a mixture of "fully heard" and "not heard at all" trials. This revealed that retro-cueing triggered an increase of more than 20% in the proportion of trials in which the secondary target was fully heard as opposed to not heard at all. We now examine these observations in relation to the previous literature on the effect of retro-cueing in audition, and then discuss in turn various interpretations.

Originality of the Present Approach Compared to Previous Studies

While the influence of retrospective cueing has been largely investigated in vision, to date only a few studies have explored this topic in audition (Backer & Alain, 2012; Chan & Alain, 2019, 2021; Lim et al., 2015). Some of these studies showed an auditory equivalent of the classical Sperling effect, using several auditory sources at various locations, as described in the introductory part (Backer & Alain, 2012). Chan and Alain (2019) investigated retrospective effects on simpler auditory scenes with only one stream: they asked participants to repeat a word embedded in white noise. The target word was paired with another word, either semantically related or not, acting as a cue. Participants' ability to report the target word increased with semantically related cues both when the cue preceded (pre-cue) and when it followed (retro-cue) the target, with a delay of up to 4 s after target presentation. This suggested that the retrospective semantic link between the target and retro-cue allowed to disambiguate the noisy representation of the target. An important difference between these findings and the current study is that, in Chan and Alain (2019), the target word always received full attention: there was a single auditory stream, which onset was always preceded by a 3 s visual countdown, so that there was no spatial nor temporal uncertainty. The target was therefore presumably always detected, but its identity could be ambiguous. It is this ambiguity that was partially resolved by the retro-cue.

Lim et al. (2015) also showed a retro-cueing effect on a consciously perceived target. In their experiment, two different syllables were played sequentially; both were clearly audible and there were no masks or distractors. The pitch of one of these syllables was to be compared to a probe played at the end of the trial, after a retention period lasting from 1 to 4 s. In one-third of the trials, a visual retro-cue informed the participant on which stimulus would be probed for the pitch discrimination task. The results showed that a valid retro-cue improved performance. Again, since both syllables were consciously perceived, the cue acted on the quality of the stored representation.

In summary, what has been clearly demonstrated up to now in the auditory modality, is the important role of retrospective attention on working memory, consistent with similar findings in the visual modality (Griffin & Nobre, 2003; Landman et al., 2003; Rerko et al., 2014; Shepherdson et al., 2018; see Souza & Oberauer, 2016 for a review). However, to the best of our knowledge, no data exist to test whether retro-cueing might also trigger a conscious perception of a previously missed target. This new question is of prime interest to arbitrate between different theories of conscious perception (Herzog et al., 2020; Sergent, 2018). The present experiments were designed to address this new question, first by using an experimental protocol—dichotic listening—in which some target words could be sometimes completely missed, and second by directly measuring conscious perception of this target word. In the following, we discuss in more detail how attention might have been deployed in the present protocol, and the rationale behind our choice of consciousness measures with regard to the existing literature.

Was Attention Split Across Ears in Our Dichotic Speech Protocol?

Understanding how attention is deployed in dichotic listening has been a major issue since the first studies introducing the paradigm (Broadbent, 1958). One interpretation postulates the existence of a selective filter, tuned to promote the processing of the attended source compared to irrelevant competing sounds (Broadbent, 1958; Deutsch & Deutsch, 1963; Treisman, 1960). The tuning of the filter may leverage acoustic cues such as the spatial disparity between talkers or differences in the characteristics of their voices (see Bronkhorst, 2015 for a review). Once the selective filter has been tuned, the sensory response to attended speech would be enhanced compared to the nonattended speech. This is consistent with recent findings showing that the neural responses correlate more strongly with acoustic features of the attended stream than the unattended one (Ding & Simon, 2012; Mesgarani & Chang, 2012). Furthermore, while participants can switch attention between speech streams following a cue, this operation takes time, consistent with the idea of a retuning of an attentional filter to a different set of acoustic features (Donald & Young, 1982; I. Koch et al., 2011; I. Koch & Lawo, 2014; Lin & Carlile, 2019).

What is the level of attention and processing devoted to the secondary channel (Holender, 1986)? Some studies argued that at least part of previous results could be explained by spontaneous attentional shifts toward the secondary stream (Colflesh & Conway, 2007; Conway et al., 2001; Dawson & Schell, 1982; Dupoux et al., 2003; Wood & Cowan, 1995). Such “dual sampling” most probably occurred in our study. This is clearly reflected by the above-chance performance on the secondary task in the no-cue condition (70.97% and 65.21% on average for Experiments 1 and 2, respectively). This level of performance was intended to avoid floor effects and optimize sensitivity to potential effects of cueing. We thus readily acknowledge that participants likely oriented their attention to the secondary stream for brief periods of time, or even split their attention during target presentation. Nevertheless, the switch cost observed on the categorization sensitivity in the primary speeded task goes against the idea that both speech streams could be simultaneously monitored in full (Figures 2A and 3A). On the contrary, it shows that the cue induced a further allocation of attentional resources toward the secondary stream, at the expense of the primary stream. This attentional boost induced a substantial increase in identification, detection and proportion of “heard” trials, even when it occurred retrospectively, 500 ms after the end of the word.

Measuring Conscious Perception

Assessing conscious perception has relied on a wide range of methods in the literature. Two main approaches are distinguished (Seth et al., 2008). A first “objective” measure of consciousness is derived from the participant’s performance in detecting the stimulus, measured for instance with the sensitivity index d' introduced by signal detection theory (Green & Swets, 1966; Macmillan & Creelman, 2005). To compute d', correct detections and false alarms are combined for a measure that is criterion-free. One of the main criticisms of this approach in the consciousness literature is that it assumes an equivalence between the threshold for conscious experience and performance on a task (Overgaard, 2017). Phenomena such as blindsight, where performance and subjective experience are dissociated, directly challenge this assumption (Lau & Passingham, 2006). A second type of measure consists in simply asking participants about their qualitative perception of the stimulus. A variety of such “subjective” measures have been used, from confidence ratings (CRs) to perceptual scales (Ramsøy & Overgaard, 2004; Sergent & Dehaene, 2004a). Sandberg et al. (2010) compared three of these methods in a perceptual task: CRs (reporting how confident one is about their response), Perceptual Awareness Scale (PAS, rating the perception of a stimulus on a 4-point scale ranging from 0 = *no experience* to 3 = *clear experience*), and post decision wagering (betting some small amounts of money on the accuracy of the response). Their results suggested that the perceptual scale produced the most sensitive and consistent measure of the actual content perceived by the participants. Perceptual scales, especially in the PAS format, have then been widely used in consciousness research for the past decade (Overgaard & Sandberg, 2021). In sum, the respective advantages and limits of different methods for probing conscious access are now well characterized, although there are still ongoing debates (Irvine, 2012; Michel, 2019; Overgaard & Sandberg, 2021).

In Experiment 2, we combined objective and subjective measures of conscious access: we included catch trials to derive a detection d', and we asked participants to rate subjective audibility on a scale (Sergent & Dehaene, 2004a; Sergent et al., 2005, 2013). These kinds of scales, which are finer-grain versions of the PAS, have been validated through numerous studies in vision and audition. These studies demonstrate that human participants use these scales in a consistent and reliable fashion and that these scales allow them to express subtle differences in the quality of their perception, for example, when shown stimuli of subtly varying strength (Del Cul et al., 2007; Sergent & Dehaene, 2004a; Sergent et al., 2005, 2013, 2021). Coexisting with this sensitivity to gradual changes in perceptual quality, we also consistently observe bimodal distributions of perceptual ratings on these scales, between zero and high ratings, for stimuli that are presented at the threshold for consciousness, in a very large variety of experimental protocols (attentional blink, visual masking, visual stimuli at threshold contrast, auditory stimuli at threshold intensity). Here we observed such bimodal distribution of audibility ratings for the secondary target words, suggesting that the corresponding perceptual content was consciously accessed on some trials, but not on other. We also deployed a quantitative model of subjective audibility ratings. Thanks to this model, we were able to infer the percentage of trials where the target word was consciously heard versus not. Through this multipronged approach that combined detection d', subjective audibility ratings and modeling of these ratings, we obtained a coherent pattern of results that strongly argues in favor of the interpretation that retro-cueing directly influenced conscious perception of the target words.

Did Retro-Cueing Influence Conscious Perception or Memory Processes?

There are alternative interpretations of the effects of retro-cueing. As briefly mentioned in the introductory part, retro-cues have been argued to facilitate recall of already perceived stimuli in both vision and audition (Souza & Oberauer, 2016). We argue that our present results are inconsistent with this “memory-only” hypothesis and rather suggest a previously unknown effect on conscious access itself in the audition.

The first line of evidence considers the influence of retro-cueing on performance as a function of the delay between target and recall. A memory account in the line of Souza and Oberauer's previous observation predicts an interaction between cueing and delay (Figure 2D): if cueing protects memory, cueing should change the slope of the memory decay, and therefore, an increase in the difference between trials with or without cueing should be observed as the retention delay increases (Figure 2D, left). In contrast, if retro-cues instead simply increases the number of trials where the target actually accesses consciousness and enters working memory, it should change the intercept of the memory decay, but not its slope (Figure 2D, right). Using Bayesian statistics, we found that our results best fitted a change in intercept but not slope (Figures 2C and 3C). This favors a perceptual interpretation over a "memory-only" interpretation.

Furthermore, Experiment 2 showed that retro-cues influenced direct measures of conscious perception (Dennett, 1992; Sandberg et al., 2010; Sergent & Dehaene, 2004a) both objective (detection d') and subjective (audibility ratings). More specifically modeling the distributions of the audibility ratings confirmed that the retro-cueing effect relied on an increase of the proportion of heard targets at the expense of missed ones, rather than an overall and gradual increase in audibility ratings.

Importantly, the conclusion that retro-cueing can change the conscious status of a past target is fully compatible with the idea that, in doing so, it induces a transfer of the target's representation from one form of memory (e.g., nonconscious sensory memory) to another form of memory (e.g., conscious working memory). The exact form of these memory systems remains to be investigated.

Taken together, our results suggest that retrospective attention can directly influence whether a past auditory stimulus is consciously heard or not. This novel observation of the auditory modality is fully consistent with what had been observed in vision (Sergent et al., 2013). The present study thus provides an essential observation in the ongoing attempt to formalize theoretical accounts of conscious perception in general, that should not be tied to the possible specificity of any single modality (Dykstra et al., 2017; Sergent et al., 2021). Moreover, by combining two influential but as yet distinct experimental paradigms, dichotic speech experiments in audition (Broadbent, 1952; Cherry, 1953) and retro-perception in vision (Sergent et al., 2013), we hope that it will initiate subsequent advances in the study of conscious perception in both fields. A specific example of the potential benefits of such a novel approach is provided next.

A Classic Result Might Be Reinterpreted in Terms of Retro-Perception

Some of the classic findings obtained in dichotic listening experiments may be reexamined in light of the present results. One of the most famous effects in the perception of complex auditory scenes, often cited in lay audience descriptions of the cocktail party phenomenon, is that people seem to be able to detect their own name within an unattended speech stream (Moray, 1959). Using a dichotic listening paradigm (Cherry, 1953) in which people were instructed to "shadow," that is repeat aloud, a speech stream presented to one ear while ignoring another speech stream presented to their other ear, Moray showed that one-third of his participants reported hearing their own name when presented to the unattended ear, while remaining largely unaware of the rest of the unattended speech. In an early account in 1964, Treisman (1964) proposed that Moray's results could be explained by considering auditory selective attention as an attenuation filter. While most of the stimuli would be successfully muted by the mechanism, some with an inherent higher saliency would still have a chance to be consciously accessed. Treisman argued that a person's own name is far from being a neutral stimulus and so could overcome the attenuation filter. Yet, the exact mechanism granting special saliency to a subliminal stimulus remained unspecified.

This intriguing result was replicated by Wood and Cowan (1995). Interestingly, in their replication, Wood and Cowan showed that the report of a person's own name was coupled with an attentional shift toward the unattended stream. Just like the pattern of error rates in our experiments, they found an increase in errors in the primary task after the onset of participants' own names, suggesting that their names induced a temporary shift of attention away from the primary stream. We argue that such a poststimulus reorientation of attention is consistent with a retro-perception account. While being processed nonconsciously initially, their name would have triggered its own retro-perception by retrospectively gaining attentional resources. Value-driven attentional shifts have already been demonstrated in dichotic listening experiments (Asutay & Västfjäll, 2016; Kim et al., 2021), supporting the hypothesis of such attentional capture by a previously unattended stimulus.

Limits of the Current Study

Some aspects of the retro-perception effect in audition remain to be further characterized. The time course of the phenomenon is one of them, as an important difference between our two experiments was the presence of an effect for the late retro-cue in one experiment but not the other. Specifically, a 1.5 s SOA diminished (Experiment 1) or totally suppressed (Experiment 2) the effect of retro-cueing. This seems to contradict estimates of echoic memory duration, suggesting that information can be held up to 10 s in this sensory store (Sams et al., 1993).

Several characteristics of our experimental procedure may account for this discrepancy. Although no interfering stimulus was played between the target and the cue in the secondary channel, an interfering word was presented in the primary channel for the late retro-cue only. This interfering stimulus may have acted as a distractor. In addition, the duration of a memory trace in echoic memory is still debated (Nees, 2016). Lower estimates of 1–2 s would be consistent with the weakness of the late retro-cue effect in our study (Darwin et al., 1972). Finally, the lack of late retro-cue effect in the second experiment might be related to the inclusion of catch trials, which reduced the cue validity. Investigations on the impact of cue validity on retro-cueing effects yielded mixed results (Gözenman et al., 2014; Gressmann & Janczyk, 2016; Gunseli et al., 2015), yet the dual task paradigm used in our study may have impeded the effect of the cue. Participants were informed that the cue was uninformative regarding the presence of a secondary target and hence could appear even if none was played in the trial. This change in validity in Experiment 2 could have led to a change in their strategy regarding the cue, lowering its capacity to trigger an endogenous shift of attention.

On a related note, there are some limitations to our analysis of the interaction between response delay and the cueing effect. Indeed, although performance does decline with response delay, this decline remains modest, and we might have lacked sensitivity to detect subtle changes in the slope with cueing.

A last open question is the exact mechanism underlying retrospective conscious access to an auditory stimulus. In an opinion paper about visual retro-perception, Sergent (2018, p. 4) argued that "by directing attention to the location of the past target while there is still a trace of this target within sensory cortices, this local information is reactivated, amplified and broadcasted within a global workspace." In the present experiments, a fairly high level of processing may have been required to perform the recognition of a spoken word. This is a potential difference with visual studies of retro-perception that investigated retro-cueing effects on the simple detection of Gabor patches. It remains to be investigated if retro-cueing operates in the initial stages of stimulus processing and/or rather in a reverse hierarchy manner (Hochstein & Ahissar, 2002; Linde-Domingo et al., 2019), triggering access to higher-level representations first.

Retro-Perception and the Fleeting Nature of Sound

We now come back to theoretical considerations, highlighting why retro-perception would be ecologically relevant for audition. In all but the simplest of acoustic scenes, listeners must dynamically grant priority to only a subpart of the sensory information received at the ears (Mesgarani & Chang, 2012; Pressnitzer & Hupé, 2006; Snyder et al., 2012). A basic but crucial feature of such a task is that, for audition, once the stimulus has passed, there is no easy way to access it again. Hence, sounds that are initially "missed" may never be recovered for further processing. This constraint is less dramatic in vision: since visual objects have a certain stability over time, observers may use the world as an external memory and do not need to maintain a detailed internal representation of the visual scene (O'Regan & Noë, 2001).

Given the temporal constraints bearing on acoustic stimuli, the existence of retrospective auditory processes would thus seem especially beneficial (Demany et al., 2010). Nevertheless, just as for vision, instances of "change deafness" have been put forward, suggesting that listeners are unable to detect a sudden change in multistream auditory scenes if they have not been pre-cued to the change (Eramudugolla et al., 2005). As discussed above, different paradigms have now shown that retrospective orienting of attention to conscious memory traces is effective, with beneficial effects on speech intelligibility (Chan & Alain, 2019). The retro-perception effects described here demonstrate yet another type of retrospective mechanism, suggesting that auditory information may not be completely lost for conscious access even if it did not reach perceptual awareness when it was first presented. Thus, orienting attention toward latent "preconscious" sensory traces (Dehaene et al., 2006) may retrospectively trigger conscious awareness, and this retro-perception effect might provide another powerful trick to overcome the moment-to-moment limitations of our attentional capacities when presented with dynamic and fleeting sound streams.

Temporal Flexibility as a General Feature of Conscious Access

The present results might prove extremely relevant in current debates about the mechanisms of conscious perception. Indeed, as mentioned in the introductory part, decoupling between the timing of conscious access and stimulus presentation is a key point to discriminate between current theories of conscious perception. The recurrent processing hypothesis (Lamme, 2006) proposes a "ballistic" sequence of events leading to the conscious experience of a stimulus. According to this model, access is granted when a first feedforward sweep triggers local recurrent loops within sensory areas, a few hundred milliseconds after sensory input. In this framework, the recurrent processing is either elicited, triggering conscious perception of the stimulus, or not, and the stimulus remains unconscious while its sensory trace fades away. The existence of retro-perception challenges this view by showing that retrospective cues may change the conscious fate of a stimulus, even if the cueing is delayed long after the first 200 ms of stimulus processing, where recurrent processing is thought to occur. Alternate models such as the Global Neuronal Workspace better accommodates this phenomenon (Dehaene & Changeux, 2011). In this model, local recurrent loops are not sufficient to allow conscious perception. The stimulus remains in a preconscious state until top-down reamplification occurs and information is shared in a widely distributed network (Dehaene et al., 2006). As a consequence, conscious perception is not time-locked to the sensory entry, but rather to this top-down interaction. Retro-perception is thus fully predicted by this decoupling between initial sensory processing and later reamplification. Specifically, a retro-cue could trigger an attentional shift to sensory traces left by a past stimulus at an arbitrary latency, thus granting them access to conscious awareness even long after sensory processing is complete (Sergent, 2018).

The present evidence, by extending the retro-perception phenomenon to the auditory domain (Rimsky-Robert et al., 2019; Sergent et al., 2013; Thibault et al., 2016; Xia et al., 2016), provides decisive evidence that temporal flexibility of access might reflect a general property of conscious perception, thus favoring a certain class of models of conscious processing such as the global workspace model.

Conclusion

In two experiments, retrospective attention was shown to influence the conscious perception of otherwise unattended speech in a dichotic listening situation. These results generalize the retro-perception phenomenon to the auditory modality. They further suggest that the mechanisms of conscious perception may be much more flexible in time than previously appreciated. This remarkable temporal flexibility might be one of the tricks with which we can develop a rich representation of a complex and changing external world, despite stringent limitations in our instantaneous attentional capacities.

References

Asbjørnsen, A. E., & Hugdahl, K. (1995). Attentional effects in dichotic listening. *Brain and Language*, *49*(3), 189–201. https://doi.org/10.1006/brln.1995.1029

Asutay, E., & Västfjäll, D. (2016). Auditory attentional selection is biased by reward cues. *Scientific Reports*, *6*(1), Article 36989. https://doi.org/10.1038/srep36989

Aydelott, J., Baer-Henney, D., Trzaskowski, M., Leech, R., & Dick, F. (2012). Sentence comprehension in competing speech: Dichotic sentence-word priming reveals hemispheric differences in auditory semantic processing. *Language and Cognitive Processes*, *27*(7–8), 1108–1144. https://doi.org/10.1080/01690965.2011.589735

Baars, B. J. (1989). *A cognitive theory of consciousness*. Cambridge University Press.

Backer, K. C., & Alain, C. (2012). Orienting attention to sound object representations attenuates change deafness. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(6), 1554–1566. https://doi.org/10.1037/a0027858

Block, N. (1995). On a confusion about a function of consciousness. *Behavioral and Brain Sciences*, *18*(2), 227–247. https://doi.org/10.1017/S0140525X00038188

Boersma, P. (2001). Praat, a system for doing phonetics by computer. *Glot International*, *5*(9/10), 341–345.

Broadbent, D. E. (1952). Listening to one of two synchronous messages. *Journal of Experimental Psychology*, *44*(1), 51–55. https://doi.org/10.1037/h0056491

Broadbent, D. E. (1958). *Perception and communication*. Pergamon Press. https://doi.org/10.1037/10037-000

Bronkhorst, A. W. (2015). The cocktail-party problem revisited: Early processing and selection of multi-talker speech. *Attention, Perception and Psychophysics*, *77*(5), 1465–1487. https://doi.org/10.3758/s13414-015-0882-9

Carrasco, M., Fuller, S., & Ling, S. (2008). Transient attention does increase perceived contrast of suprathreshold stimuli: A reply to Prinzmetal, Long, and Leonhardt (2008). *Perception and Psychophysics*, *70*(7), 1151–1164. https://doi.org/10.3758/PP.70.7.1151

Chan, T. M. V., & Alain, C. (2019). Listening back in time: Does attention to memory facilitate word-in-noise identification? *Attention, Perception and Psychophysics*, *81*(1), 253–269. https://doi.org/10.3758/s13414-018-1586-8

Chan, T. M. V., & Alain, C. (2021). Brain indices associated with semantic cues prior to and after a word in noise. *Brain Research*, *1751*, Article 147206. https://doi.org/10.1016/j.brainres.2020.147206

Cherry, E. C. (1953). Some experiments on the recognition of speech, with one and with two ears. *The Journal of the Acoustical Society of America*, *25*(5), 975–979. https://doi.org/10.1121/1.1907229

Colflesh, G. J. H., & Conway, A. R. A. (2007). Individual differences in working memory capacity and divided attention in dichotic listening. *Psychonomic Bulletin and Review*, *14*(4), 699–703. https://doi.org/10.3758/BF03196824

Conway, A. R. A., Cowan, N., & Bunting, M. F. (2001). The cocktail party phenomenon revisited: The importance of working memory capacity. *Psychonomic Bulletin and Review*, *8*(2), 331–335. https://doi.org/10.3758/BF03196169

Cowan, N. (1999). An embedded-processes model of working memory. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 62–101). Cambridge University Press. https://doi.org/10.1017/CBO9781139174909.006

Darwin, C. J., Turvey, M. T., & Crowder, R. G. (1972). An auditory analogue of the sperling partial report procedure: Evidence for brief auditory storage. *Cognitive Psychology*, *3*(2), 255–267. https://doi.org/10.1016/0010-0285(72)90007-2

Dawson, M. E., & Schell, A. M. (1982). Electrodermal responses to attended and nonattended significant stimuli during dichotic listening. *Journal of Experimental Psychology: Human Perception and Performance*, *8*(2), 315–324. https://doi.org/10.1037/0096-1523.8.2.315

Dehaene, S., & Changeux, J.-P. (2011). Experimental and theoretical approaches to conscious processing. *Neuron*, *70*(2), 200–227. https://doi.org/10.1016/j.neuron.2011.03.018

Dehaene, S., Changeux, J.-P., Naccache, L., Sackur, J., & Sergent, C. (2006). Conscious, preconscious, and subliminal processing: A testable taxonomy. *Trends in Cognitive Sciences*, *10*(5), 204–211. https://doi.org/10.1016/j.tics.2006.03.007

Dehaene, S., & Naccache, L. (2001). Towards a cognitive neuroscience of consciousness: Basic evidence and a workspace framework. *Cognition*, *79*(1–2), 1–37. https://doi.org/10.1016/S0010-0277(00)00123-2

Del Cul, A., Baillet, S., Dehaene, S., & Posner, M. (2007). Brain dynamics underlying the nonlinear threshold for access to consciousness. *PLoS Biology*, *5*(10), Article e260. https://doi.org/10.1371/journal.pbio.0050260

Demany, L., Semal, C., Cazalets, J.-R., & Pressnitzer, D. (2010). Fundamental differences in change detection between vision and audition. *Experimental Brain Research*, *203*(2), 261–270. https://doi.org/10.1007/s00221-010-2226-2

Dennett, D. C. (1992). *Consciousness explained*. Penguin.

Dennett, D. C., & Kinsbourne, M. (1992). Time and the observer: The where and when of consciousness in the brain. *Behavioral and Brain Sciences*, *15*(2), 183–201. https://doi.org/10.1017/S0140525X00068229

Deutsch, J. A., & Deutsch, D. (1963). Some theoretical considerations. *Psychological Review*, *70*(1), 80–90. https://doi.org/10.1037/h0039515

Ding, N., & Simon, J. Z. (2012). Neural coding of continuous speech in auditory cortex during monaural and dichotic listening. *Journal of Neurophysiology*, *107*(1), 78–89. https://doi.org/10.1152/jn.00297.2011

Donald, M. W., & Young, M. J. (1982). A time-course analysis of attentional tuning of the auditory evoked response. *Experimental Brain Research*, *46*(3), 357–367. https://doi.org/10.1007/BF00238630

Dupoux, E., Kouider, S., & Mehler, J. (2003). Lexical access without attention? Explorations using dichotic priming. *Journal of Experimental Psychology: Human Perception and Performance*, *29*(1), 172–184. https://doi.org/10.1037/0096-1523.29.1.172

Dykstra, A. R., Cariani, P. A., & Gutschalk, A. (2017). A roadmap for the study of conscious audition and its neural basis. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *372*(1714), Article 20160103. https://doi.org/10.1098/rstb.2016.0103

Eich, E. (1984). Memory for unattended events: Remembering with and without awareness. *Memory and Cognition*, *12*(2), 105–111. https://doi.org/10.3758/BF03198423

Eramudugolla, R., Irvine, D. R. F., McAnally, K. I., Martin, R. L., & Mattingley, J. B. (2005). Directed attention eliminates ‘change deafness’ in complex auditory scenes. *Current Biology*, *15*(12), 1108–1113. https://doi.org/10.1016/j.cub.2005.05.051

Gaillard, R., Dehaene, S., Adam, C., Clémenceau, S., Hasboun, D., Baulac, M., Cohen, L., Naccache, L., & Ungerleider, L. (2009). Converging intracranial markers of conscious access. *PLoS Biology*, *7*(3), Article e1000061. https://doi.org/10.1371/journal.pbio.1000061

Gözenman, F., Tanoue, R. T., Metoyer, T., & Berryhill, M. E. (2014). Invalid retro-cues can eliminate the retro-cue benefit: Evidence for a hybridized account. *Journal of Experimental Psychology: Human Perception and Performance*, *40*(5), 1748–1754. https://doi.org/10.1037/a0037474

Green, D. M., & Swets, J. A. (1966). *Signal detection theory and psychophysics*. Wiley. https://books.google.fr/books?id=NMa7zQEACAAJ7

Gressmann, M., & Janczyk, M. (2016). The (un)clear effects of invalid retro-cues. *Frontiers in Psychology*, *7*, Article 244. https://doi.org/10.3389/fpsyg.2016.00244

Griffin, I. C., & Nobre, A. C. (2003). Orienting attention to locations in internal representations. *Journal of Cognitive Neuroscience*, *15*(8), 1176–1194. https://doi.org/10.1162/089892903322598139

Gunseli, E., van Moorselaar, D., Meeter, M., & Olivers, C. N. L. (2015). The reliability of retro-cues determines the fate of noncued visual working memory representations. *Psychonomic Bulletin and Review*, *22*(5), 1334–1341. https://doi.org/10.3758/s13423-014-0796-x

Hanley, J. A., & McNeil, B. J. (1982). The meaning and use of the area under a receiver operating characteristic (ROC) curve. *Radiology*, *143*(1), 29–36. https://doi.org/10.1148/radiology.143.1.7063747

Herzog, M. H., Drissi-Daoudi, L., & Doerig, A. (2020). All in good time: Long-lasting postdictive effects reveal discrete perception. *Trends in Cognitive Sciences*, *24*(10), 826–837. https://doi.org/10.1016/j.tics.2020.07.001

Hochstein, S., & Ahissar, M. (2002). View from the top: Hierarchies and reverse hierarchies in the visual system. *Neuron*, *36*(5), 791–804. https://doi.org/10.1016/S0896-6273(02)01091-7

Holender, D. (1986). Semantic activation without conscious identification in dichotic listening, parafoveal vision, and visual masking: A survey and appraisal. *Behavioral and Brain Sciences*, *9*(1), 1–23. https://doi.org/10.1017/S0140525X00021269

Irvine, E. (2012). Old problems with new measures in the science of consciousness. *The British Journal for the Philosophy of Science*, *63*(3), 627–648. https://doi.org/10.1093/bjps/axs019

Kim, A. J., Lee, D. S., & Anderson, B. A. (2021). The influence of threat on the efficiency of goal-directed attentional control. *Psychological Research*, *85*(3), 980–986. https://doi.org/10.1007/s00426-020-01321-4

Kimura, D. (1961). Cerebral dominance and the perception of verbal stimuli. *Canadian Journal of Psychology/Revue Canadienne de Psychologie*, *15*(3), 166–171. https://doi.org/10.1037/h0083219

Kinchla, R. A., Chen, Z., & Evert, D. (1995). Precue effects in visual search: Data or resource limited? *Perception and Psychophysics*, *57*(4), 441–450. https://doi.org/10.3758/BF03213070

Koch, C., & Tsuchiya, N. (2007). Attention and consciousness: Two distinct brain processes. *Trends in Cognitive Sciences*, *11*(1), 16–22. https://doi.org/10.1016/j.tics.2006.10.012

Koch, I., & Lawo, V. (2014). Exploring temporal dissipation of attention settings in auditory task switching. *Attention, Perception and Psychophysics*, *76*(1), 73–80. https://doi.org/10.3758/s13414-013-0571-5

Koch, I., Lawo, V., Fels, J., & Vorländer, M. (2011). Switching in the cocktail party: Exploring intentional control of auditory selective attention. *Journal of Experimental Psychology: Human Perception and Performance*, *37*(4), 1140–1147. https://doi.org/10.1037/a0022189

Lamme, V. A. F. (2003). Why visual attention and awareness are different. *Trends in Cognitive Sciences*, *7*(1), 12–18. https://doi.org/10.1016/S1364-6613(02)00013-X

Lamme, V. A. F. (2006). Towards a true neural stance on consciousness. *Trends in Cognitive Sciences*, *10*(11), 494–501. https://doi.org/10.1016/j.tics.2006.09.001

Landman, R., Spekreijse, H., & Lamme, V. A. F. (2003). Large capacity storage of integrated objects before change blindness. *Vision Research*, *43*(2), 149–164. https://doi.org/10.1016/S0042-6989(02)00402-9

Lau, H. C., & Passingham, R. E. (2006). Relative blindsight in normal observers and the neural correlate of visual consciousness. *Proceedings of the National Academy of Sciences of the United States of America*, *103*(49), 18763–18768. https://doi.org/10.1073/pnas.0607716103

Lim, S.-J., Wöstmann, M., & Obleser, J. (2015). Selective attention to auditory memory neurally enhances perceptual precision. *The Journal of Neuroscience*, *35*(49), 16094–16104. https://doi.org/10.1523/JNEUROSCI.2674-15.2015

Lin, G., & Carlile, S. (2019). The effects of switching non-spatial attention during conversational turn taking. *Scientific Reports*, *9*(1), Article 8057. https://doi.org/10.1038/s41598-019-44560-1

Linde-Domingo, J., Treder, M. S., Kerrén, C., & Wimber, M. (2019). Evidence that neural information flow is reversed between object perception and object reconstruction from memory. *Nature Communications*, *10*(1), Article 179. https://doi.org/10.1038/s41467-018-08080-2

Macmillan, N. A., & Creelman, C. D. (2005). *Detection theory: A user's guide* (2nd ed.). Lawrence Erlbaum Associates.

Mashour, G. A., Roelfsema, P., Changeux, J.-P., & Dehaene, S. (2020). Conscious processing and the global neuronal workspace hypothesis. *Neuron*, *105*(5), 776–798. https://doi.org/10.1016/j.neuron.2020.01.026

Mesgarani, N., & Chang, E. F. (2012). Selective cortical representation of attended speaker in multi-talker speech perception. *Nature*, *485*(7397), 233–236. https://doi.org/10.1038/nature11020

Michel, M. (2019). The mismeasure of consciousness: A problem of coordination for the Perceptual Awareness Scale. *Philosophy of Science*, *86*(5), 1239–1249. https://doi.org/10.1086/705509

Mondor, T. A., & Amirault, K. J. (1998). Effect of same- and different-modality spatial cues on auditory and visual target identification. *Journal of Experimental Psychology: Human Perception and Performance*, *24*(3), 745–755. https://doi.org/10.1037/0096-1523.24.3.745

Mondor, T. A., & Breau, L. M. (1999). Facilitative and inhibitory effects of location and frequency cues: Evidence of a modulation in perceptual sensitivity. *Perception and Psychophysics*, *61*(3), 438–444. https://doi.org/10.3758/BF03211964

Mondor, T. A., & Zatorre, R. J. (1995). Shifting and focusing auditory spatial attention. *Journal of Experimental Psychology: Human Perception and Performance*, *21*(2), 387–409. https://doi.org/10.1037/0096-1523.21.2.387

Moray, N. (1959). Attention in dichotic listening: Affective cues and the influence of instructions. *The Quarterly Journal of Experimental Psychology*, *11*(1), 56–60. https://doi.org/10.1080/17470215908416289

Nees, M. A. (2016). Have we forgotten auditory sensory memory? Retention intervals in studies of nonverbal auditory working memory. *Frontiers in Psychology*, *7*, Article 1892. https://doi.org/10.3389/fpsyg.2016.01892

Oberauer, K. (2002). Access to information in working memory: Exploring the focus of attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *28*(3), 411–421. https://doi.org/10.1037/0278-7393.28.3.411

Oberauer, K. (2009). Design for a working memory. In B. H. Ross (Ed.) *Psychology of learning and motivation* (Vol. 51, pp. 45–100). Academic Press. https://doi.org/10.1016/S0079-7421(09)51002-X

O'Regan, J. K., & Noë, A. (2001). A sensorimotor account of vision and visual consciousness. *Behavioral and Brain Sciences*, *24*(5), 939–973. https://doi.org/10.1017/S0140525X01000115

Overgaard, M. (2017). The status and future of consciousness research. *Frontiers in Psychology*, *8*, Article 1719. https://doi.org/10.3389/fpsyg.2017.01719

Overgaard, M., & Sandberg, K. (2021). The Perceptual Awareness Scale-recent controversies and debates. *Neuroscience of Consciousness*, *2021*(1), Article niab044. https://doi.org/10.1093/nc/niab044

Pressnitzer, D., & Hupé, J.-M. (2006). Temporal dynamics of auditory and visual bistability reveal common principles of perceptual organization. *Current Biology*, *16*(13), 1351–1357. https://doi.org/10.1016/j.cub.2006.05.054

Prinzmetal, W., Long, V., & Leonhardt, J. (2008). Involuntary attention and brightness contrast. *Perception and Psychophysics*, *70*(7), 1139–1150. https://doi.org/10.3758/PP.70.7.1139

Ramsøy, T. Z., & Overgaard, M. (2004). Introspection and subliminal perception. *Phenomenology and the Cognitive Sciences*, *3*(1), 1–23. https://doi.org/10.1023/B:PHEN.0000041900.30172.e8

Rerko, L., Souza, A. S., & Oberauer, K. (2014). Retro-cue benefits in working memory without sustained focal attention. *Memory and Cognition*, *42*(5), 712–728. https://doi.org/10.3758/s13421-013-0392-8

Rimsky-Robert, D., Störmer, V., Sackur, J., & Sergent, C. (2019). Retrospective auditory cues can improve detection of near-threshold visual targets. *Scientific Reports*, *9*(1), Article 18966. https://doi.org/10.1038/s41598-019-55261-0

Sams, M., Hari, R., Rif, J., & Knuutila, J. (1993). The human auditory sensory memory trace persists about 10 s: Neuromagnetic evidence. *Journal of Cognitive Neuroscience*, *5*(3), 363–370. https://doi.org/10.1162/jocn.1993.5.3.363

Sandberg, K., Timmermans, B., Overgaard, M., & Cleeremans, A. (2010). Measuring consciousness: Is one measure better than the other? *Consciousness and Cognition*, *19*(4), 1069–1078. https://doi.org/10.1016/j.concog.2009.12.013

Sergent, C. (2018). The offline stream of conscious representations. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *373*(1755), Article 20170349. https://doi.org/10.1098/rstb.2017.0349

Sergent, C., Baillet, S., & Dehaene, S. (2005). Timing of the brain events underlying access to consciousness during the attentional blink. *Nature Neuroscience*, *8*(10), 1391–1400. https://doi.org/10.1038/nn1549

Sergent, C., Corazzol, M., Labouret, G., Stockart, F., Wexler, M., King, J.-R., Meyniel, F., & Pressnitzer, D. (2021). Bifurcation in brain dynamics reveals a signature of conscious processing independent of report. *Nature Communications*, *12*(1), Article 1149. https://doi.org/10.1038/s41467-021-21393-z

Sergent, C., & Dehaene, S. (2004a). Is consciousness a gradual phenomenon? Evidence for an all-or-none bifurcation during the attentional blink. *Psychological Science*, *15*(11), 720–728. https://doi.org/10.1111/j.0956-7976.2004.00748.x

Sergent, C., & Dehaene, S. (2004b). Neural processes underlying conscious perception: Experimental findings and a global neuronal workspace framework. *Journal of Physiology, Paris*, *98*(4–6), 374–384. https://doi.org/10.1016/j.jphysparis.2005.09.006

Sergent, C., & Naccache, L. (2012). Imaging neural signatures of consciousness: “What,” “when,” “where” and “how” does it work? *Archives Italiennes de Biologie*, *150*(2–3), 91–106. https://doi.org/10.4449/aib.v150i2.1270

Sergent, C., Wyart, V., Babo-Rebelo, M., Cohen, L., Naccache, L., & Tallon-Baudry, C. (2013). Cueing attention after the stimulus is gone can retrospectively trigger conscious perception. *Current Biology*, *23*(2), 150–155. https://doi.org/10.1016/j.cub.2012.11.047

Seth, A. K., Dienes, Z., Cleeremans, A., Overgaard, M., & Pessoa, L. (2008). Measuring consciousness: Relating behavioural and neurophysiological approaches. *Trends in Cognitive Sciences*, *12*(8), 314–321. https://doi.org/10.1016/j.tics.2008.04.008

Shepherdson, P., Oberauer, K., & Souza, A. S. (2018). Working memory load and the retro-cue effect: A diffusion model account. *Journal of Experimental Psychology: Human Perception and Performance*, *44*(2), 286–310. https://doi.org/10.1037/xhp0000448

Snyder, J. S., Gregg, M. K., Weintraub, D. M., & Alain, C. (2012). Attention, awareness, and the perception of auditory scenes. *Frontiers in Psychology*, *3*, Article 15. https://doi.org/10.3389/fpsyg.2012.00015

Souza, A. S., & Oberauer, K. (2016). In search of the focus of attention in working memory: 13 years of the retro-cue effect. *Attention, Perception and Psychophysics*, *78*(7), 1839–1860. https://doi.org/10.3758/s13414-016-1108-5

Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs*, *74*(11), 1–29. https://doi.org/10.1037/h0093759

Thibault, L., van den Berg, R., Cavanagh, P., Sergent, C., & de Lange, F. P. (2016). Retrospective attention gates discrete conscious access to past sensory stimuli. *PLoS ONE*, *11*(2), Article e0148504. https://doi.org/10.1371/journal.pone.0148504

Treisman, A. M. (1960). Contextual cues in selective listening. *The Quarterly Journal of Experimental Psychology*, *12*(4), 242–248. https://doi.org/10.1080/17470216008416732

Treisman, A. M. (1964). Monitoring and storage of irrelevant messages in selective attention. *Journal of Verbal Learning and Verbal Behavior*, *3*(6), 449–459. https://doi.org/10.1016/S0022-5371(64)80015-3

Vogel, E. K., Woodman, G. F., & Luck, S. J. (2005). Pushing around the locus of selection: Evidence for the flexible-selection hypothesis. *Journal of Cognitive Neuroscience*, *17*(12), 1907–1922. https://doi.org/10.1162/089892905775008599

Wood, N. L., & Cowan, N. (1995). The cocktail party phenomenon revisited: How frequent are attention shifts to one’s name in an irrelevant auditory channel? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *21*(1), 255–260. https://doi.org/10.1037/0278-7393.21.1.255

Wood, N. L., Stadler, M. A., & Cowan, N. (1997). Is there implicit memory without attention? A reexamination of task demands in Eich’s (1984) procedure. *Memory and Cognition*, *25*(6), 772–779. https://doi.org/10.3758/BF03211320

Woodman, G. F., Vecera, S. P., & Luck, S. J. (2003). Perceptual organization influences visual working memory. *Psychonomic Bulletin and Review*, *10*(1), 80–87. https://doi.org/10.3758/BF03196470

Xia, Y., Morimoto, Y., & Noguchi, Y. (2016). Retrospective triggering of conscious perception by an interstimulus interaction. *Journal of Vision*, *16*(7), Article 3. https://doi.org/10.1167/16.7.3

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