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Replicating and extending hemispheric asymmetries in auditory distraction: no metacognitive awareness for the left-ear disadvantage for changing-state sounds

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ABSTRACT

In two experiments investigating hemispheric asymmetries in auditory distraction, the spatial location of to-be-ignored sound was manipulated. Prior studies indicated a left-ear disadvantage for changing-state sequences during short-term serial recall but lacked a direct measure of the changing-state effect. Experiment 1 compared changing-state with steady-state sequences in a visual-verbal serial recall task, confirming that left-ear disruption resulted from the acoustically varying nature of the sound, emphasizing right hemisphere dominance for processing acoustic variation in unattended stimuli. Experiment 2 replicated these findings and explored participants' metacognitive awareness of auditory distractors' disruptive potential. While participants were aware that changing-state sequences were more disruptive than steady-state sequences, they lacked awareness of the left-ear disadvantage. The study suggests individuals have metacognitive awareness of the disruptive impact of changing-state over steady-state sound but not of the accompanying left-ear disadvantage, raising implications for theoretical accounts of auditory distraction.

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Audition is often regarded as the *sentinel of the senses,* owing to the lack of intrinsic physical mechanisms to adjust the probability of perceiving auditory-sensory stimuli (Hapeshi & Jones, 1992). As opposed to vision, for instance, hearing cannot be "switched off": whereas the visual field is spatially bounded, audition is a far-reaching sense that captures multiple sources of information from all directions, irrespective of head position (King & Nelken, 2009). In addition, the processing of the auditory scene cannot be interrupted since humans are unable to readily "shut" their ears in the same way they can close their eyes. It is thought that such unique properties of hearing serve a survival function, as they allow for the detection of sudden fluctuations in energy which may necessitate an immediate response (Banbury et al., 2001). This is true not only in instances where a threat is present, but also in more innocuous situations where the shift signifies that previously ignored sounds begin to carry valuable information (Yadav et al., 2017). Designed in the heat of evolutionary adaptation to signal distant and hitherto unnoticed events, the auditory system is therefore highly advantageous (Macken, 2014). This continuous registering of sound is, however, inevitably accompanied by undesired distraction. Indeed, during everyday mental performance, the capacity to concentrate on a task might be threatened by extraneous auditory stimuli which can intrude on awareness without hindrance (Lavie, 2005). Furthermore, certain sounds have greater disruptive potential depending on their spatial location and subsequent neural activation, given that each

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cerebral hemisphere represents a functionally distinct processing unit (Kimura, 1967). The encoding preferences of the left and right sides of the brain (Tervaniemi & Hugdahl, 2003) thus give rise to hemispheric asymmetries in auditory distraction.

The extent to which an auditory stimulus is recognised as distracting can be influenced by metacognitive beliefs about the disruptive effects it produces on cognitive performance (Bell et al., 2021). For instance, while studying, someone might perceive constant drilling noise as a source of disruption and hence implement measures to minimise it, but purposely listen to music to enhance their concentration. Recent evidence suggests that individuals can accurately judge the detrimental impact of task-irrelevant sound on short-term memory (Bell et al., 2021), as demonstrated, for example, by their subjective confidence regarding the accuracy of their short-term memory performance when visual memoranda are presented alongside auditory stimuli (Kattner & Bryce, 2022). However, whether this metacognitive awareness extends to hemispheric asymmetry effects in auditory distraction remains unexplored and represents one focus of the present paper.

Researchers have paid special attention to the study of serial short-term memory to better understand the influence of distracting sound on mental processes. The standard and most widely used paradigm for exploring this cognitive function is the visual-verbal serial recall task, whereby sequences of typically six to eight visual-verbal items (e.g. letters, digits) are displayed consecutively on a screen, and must be immediately repeated in the exact order of presentation (Hughes & Jones, 2001). The mere presence of to-be-ignored sounds during the encoding, or retention, of visual-verbal items produces impairments of up to 20–50% compared to a quiet control condition (Hughes et al., 2005).

This phenomenon, termed the *irrelevant sound effect*, is firmly established in the cognitive psychology literature, and emerges when the to-be-recalled material is accompanied by unwanted auditory distractors (e.g. Beaman & Jones, 1997; Jones & Macken, 1993). The presence of irrelevant sound leads to a substantial decrease in short-term memory performance, even if the sound is barely audible and participants are instructed to deliberately ignore it (e.g. Jones & Macken, 1995a; Tremblay & Jones, 1999). Therefore, due to the obligatory processing of the auditory environment, the detrimental impact of extraneous noise on cognition is independent of sound intensity (Ellermeier & Zimmer, 2014). However, recent research (Alikadic & Röer, 2022) suggests that louder sounds (75 dB(A) compared with 45 dB(A)) produce greater disruption. More important for determining the extent of deficits in serial recall, however, is the number of sudden changes in the tempo, frequency, or amplitude of the acoustic stream, giving rise to the well-documented *changing-state effect* (CSE; Jones et al., 1992).

Considered as the empirical signature of the irrelevant sound effect, the CSE refers to the impairment of visual-verbal short-term memory by changing-state sequences containing acoustically varying items (e.g. N-O-P-Q-R …), relative to steady-state sequences comprising a single repeated distractor (e.g. N-N-N-N-N … ; Jones et al., 2004; Jones & Macken, 1995b). Crucially, the CSE is independent of the intensity of the distractors (Alikadic & Röer, 2022). Furthermore, when speech and non-speech sounds incorporate the same amount of acoustic fluctuation, they yield equivalent levels of distraction (Tremblay et al., 2000). Likewise, a comparable magnitude of disruption to serial recall performance occurs from a language spoken by participants, relative to a language that is foreign to them (Salamé & Baddeley, 1982; Ueda et al., 2019). It thus becomes apparent that the semantic content of task-irrelevant sounds is generally inconsequential within the serial recall setting (Jones et al., 1990; Röer et al., 2014), unless it conveys material such as one's own name, emotional words that promote attentional capture (Marsh et al., 2018; Röer et al., 2017), an isolated sentence (Hughes & Marsh, 2017), or items that are inconsistent with the semantic context provided by the auditory sequence (Röer et al., 2019; Vachon et al., 2020). Such post-categorical effects of to-be-ignored sound are not integral to the acoustically driven irrelevant sound effect and, unlike the CSE that is restricted to visual-verbal serial recall, are typically observable across numerous empirical settings (see e.g. Marsh et al., 2018; Vachon et al., 2020).

That the CSE is a joint product of the acoustically varying nature of the to-be-ignored sound and the characteristics of the prevailing focal task coheres with a key prediction of the duplex-mechanism account (e.g. Hughes, 2014). On this view, the CSE is caused by interference-by-process: a clash between two order-based processes that compete for the control of action (Hughes et al., 2007). More specifically, the automatic processing of order in the to-be-ignored material interferes with the conscious ordering (i.e. serial rehearsal) of the to-be-recalled items in the primary task (Hughes & Marsh, 2017; Jones & Tremblay, 2000). The CSE is thus seen as an inevitable outcome of the involuntary seriation of auditory stimuli (Hughes, 2014). This explains why the CSE is observed when seriation is a core element of the primary task, but not when the focal task does not necessitate seriation, such as identifying a missing item from a well-known set (i.e. the missing-item task; Beaman & Jones, 1997; Hughes & Marsh, 2017; Jones & Macken, 1993; Marsh et al., 2018). According to the duplex-mechanism account, the CSE is qualitatively distinct from another form of auditory distraction that has been coined the *deviation effect* (Hughes et al., 2005; Lange, 2005; Sörqvist, 2010), whereby visual-verbal serial recall is disrupted by a sequence comprising a sound that deviates from the recent auditory past (e.g. A-A-A-B-A) as compared with a sequence without such a deviation (e.g. A-A-A-A-A). In this case, rather than interference-by-process, an attentional capture mechanism is triggered due to unexpected or inconsistent changes in auditory stimulation following repetitive sound patterns, and hence the focus of attention is involuntarily redirected towards the deviant event (Hughes et al., 2007).

The basis for proposing that the CSE and deviation effect are qualitatively distinct auditory distraction effects is perhaps most convincingly demonstrated through analyses of task-sensitivity. Whereas the CSE typically arises when seriation is a central feature of the focal task (Beaman & Jones, 1997; Hughes et al., 2007), the deviation effect is observed in a variety of qualitatively distinct paradigms wherein the focal task does not necessitate serial rehearsal such as the missing-item task (Hughes et al., 2007; Vachon et al., 2017).

Despite these task-sensitivity differences, proponents of the unitary account (Bell et al., 2012, 2021; Elliott, 2002) continue to challenge the conceptualisation that the CSE and the deviation effect are qualitatively distinct. On the unitary account, any novel sound presented in an irrelevant auditory stream has the potential to reorient the attentional focus and impair performance (Bell et al., 2012; Cowan, 1999; Elliott, 2002). Based on this perspective, changing-state auditory stimuli (e.g. N-O-P-Q-R …) produce attention orienting as each distractor item diverges from the preceding succession of sounds registered in short-term memory (Bell et al., 2012). Similarly, deviant sounds within a steady-state sequence (e.g. N-N-O-N-N …) capture attention as they differ from the auditory context in which they are embedded (Bell et al., 2019).

To tease apart the duplex-mechanism and unitary accounts, some researchers have recently adopted a metacognitive approach (Bell et al., 2021; Kattner & Bryce, 2022). Since, on the duplex-mechanism account (e.g. Hughes, 2014), it is the automatic pre-attentive processing (perceptual streaming) of sequences that gives rise to the CSE, it is argued that participants should be metacognitively unaware of the greater disruption of changing- over steady-state sequences (Bell et al., 2021; Kattner & Bryce, 2022). Bell et al. (2021) argue that, because the perceptual streaming process occurs without awareness and is stimulus-driven as compared with goal-dependent (see Jacoby et al., 1993), the duplex-mechanism account predicts that participants should be unaware of the disruption to their performance that is produced by interference-by-process. However, because the duplex-mechanism account asserts that attentional capture underpins the deviation effect, Bell et al. (2021) propose that participants should show metacognitive awareness of this effect (Bell et al., 2021; see also Kattner & Bryce, 2022). Taken together, on this line of reasoning, participants should be metacognitively aware of the deviation effect, yet metacognitively unaware of the CSE. Further, since the unitary account assumes that both the CSE and the deviation effect are underpinned by attentional capture (Bell et al., 2012; 2019), participants should be equivalently metacognitively aware of both effects.

Across two recent studies (Bell et al., 2021; Kattner & Bryce, 2022), participants have been shown to be equally metacognitively aware of both the CSE and deviation effects—a result interpreted as consistent with the unitary account (Bell et al., 2012, 2019) and at odds with the duplex-mechanism account (Hughes, 2014). We return to the issue of metacognitive awareness of differential effects of auditory distraction in Experiment 2.

Hemispheric asymmetries in auditory distraction

An additional approach to distinguishing whether the CSE reflects an interference-by-process or attentional capture may stem from the manipulation of spatial location of irrelevant sound, based on the hemispheric lateralisation of auditory perception. A substantial body of research illustrates patterns of contralateral, rather than ipsilateral, activation during auditory stimulation, resulting in sound presented to the left ear being processed by the right hemisphere and vice versa (Jäncke et al., 2002). In the context of a dichotic listening task, phonological targets that are monaurally presented to the right ear are more accurately detected or shadowed than when presented to the left ear (Kimura, 1961b; Kinsbourne, 1970), but this pattern does not extend to musical stimuli (Hugdahl et al., 1999). Further, this differential activation extends to monaural stimulation with faster and more efficient activation of the contralateral hemisphere compared with binaural stimulation (Jäncke et al., 2002; Suzuki et al., 2000). This pattern aligns with data from neuroimaging and neuropsychological patients that conclude that left hemisphere processing underpins immediate verbal memory (Baddeley, 2003; Henson, 2001), with speech presented to the right ear being transmitted to verbal memory relatively directly. At odds with this *right-ear advantage* (Kimura, 1961a, b) in the context of dichotic listening, irrelevant sound presented to the left ear is more damaging to visual-verbal serial recall than that presented to the right ear or dichotically (Hadlington et al., 2004; 2006), i.e. a *left-ear disadvantage* (Hadlington et al., 2004). The two findings are reconciled by the notion that right-ear input is preferentially received by the left hemisphere, which is specialised for language functions and lexico-semantic information (Beaman et al., 2007), whereas left-ear input is preferentially received by the right hemisphere, which is implicated in the processing of acoustic features such as changes within complex auditory patterns (Poeppel et al., 2004), including prosodic and melodic changes (Fries & Swihart, 1990; Joseph, 1988; Mazzucchi et al., 1981; Zatorre et al., 1994). In this way, these differences in hemispheric processing are believed to produce a right-ear or left-ear advantage in tasks requiring linguistic or non-linguistic sound processing respectively (Hugdahl et al., 2009).

In the context of visual-verbal serial recall, Hadlington et al. (2004; 2006) build a body of evidence across two studies and eight experiments that support the idea that the right hemisphere has a principal role in the obligatory perception and processing of changing-state auditory information, as indexed by the impact of irrelevant sound on visual-verbal serial recall even when participants are instructed to ignore it. For instance, Hadlington et al. (2004) demonstrated that changing-state sounds (e.g. sequences of letters, or sine-tones) disrupted short-term memory on a serial probe task to a greater extent when presented to the left ear, relative to the right ear and both ears (Hadlington et al., 2004). Importantly, this left-ear disadvantage produced by sequences of letters and tones depended on focal task requirements, being observed for a mental arithmetic task—which necessitates seriation to maintain the sequence of figures and operator (Hadlington et al., 2006, Experiment 1a [letters], Experiment 1b [tones])—but not a missing-item task (Hadlington et al., 2006, Experiment 2a [letters], Experiment 2b [tones]), which does not necessitate seriation (Beaman & Jones, 1997; Jones & Macken, 1993; Marsh et al., 2018). This supports the notion that the left-ear disadvantage reflects a clash between the seriation process automatically applied to the sound, and the deliberate seriation process required for serial recall. Further, in the context of visual-verbal serial recall, Hadlington et al. (2006) found a left-ear disadvantage for irrelevant sound sequences comprising item-to-item pitch changes (Experiment 3b), inter-stimulus interval changes (of a repeated item; Experiment 3c), and item-to-item pitch changes with variable inter-stimulus interval changes (Experiment 3d). In contrast, however, the left-ear disadvantage did not emerge for steady-state sequences comprising a repeated utterance (Experiment 3a), which suggests that the primary factor contributing to enhanced disruption via left-ear presentation is the presence of discrete variations in the irrelevant auditory stream.

Across several of their experiments, Hadlington et al. (2004; 2006) reported that the impairment of short-term memory performance by irrelevant sound was greater when the sound was presented to the left ear as compared with both ears. This aligns with the view that excitation produced in contralateral pathways can produce inhibition in ipsilateral pathways (Yvert et al., 1998): with binaural presentation, two ipsilateral inhibitory pathways are activated, while monaural stimulation activates only one. Therefore, dichotic presentation results in greater inhibition of the flow of irrelevant information due to increased ipsilateral activation, thereby attenuating its disruptive effect.

Based on the foregoing, one could argue that, compared to binaural presentation, the disruption observed with left-ear presentation reflects a purer expression of a CSE, whereby a less restricted (uninhibited) flow of irrelevant processing (e.g. obligatory perception of changing-state sequences) can flood into the right hemispheric-based motor-articulatory processes that subserve the seriation of visual-verbal stimuli for serial recall. This would be consistent with the finding that the left-ear disadvantage emerged for tasks that required motor-articulatory processes for seriating visual material (e.g. serial probe; Hadlington et al., 2004; mental arithmetic and serial recall; Hadlington et al., 2006), but not the missing-item task (Hadlington et al., 2006, Experiment 2), for which performance is independent of the capacity to serially rehearse. The missing-item task, for example, is immune to disruption via articulatory suppression (Klapp et al., 1983), which is typically assumed to impair serial rehearsal processes (Baddeley, 2007; Jones et al., 2006; Murray, 1968). On the perspective of the duplex-mechanism account, the left-ear disadvantage may be indicative of an increased interference-by-process in the right hemisphere for situations wherein changing-state sequences are presented to the left ear, coupled with the focal task requirement for serial recall.

Experiment 1

Despite Hadlington et al.'s (2004; 2006) convincing arguments for an enhanced CSE with left-ear against right-ear and dichotic presentation (Hadlington et al., 2004; 2006), there is a reason why their conclusions be tempered: Hadlington et al. (2004; 2006) reported a left-ear disadvantage based on the comparison of changing-state and quiet trials, but did not compare changing- with steady-state sequences within the same experiment, nor did they perform any cross-experiment analysis (e.g. Experiment 3a with Experiment 3b). Therefore, whether the additional disruption produced via left-ear presentation was attributable to sound per se regardless of its varying acoustic composition has yet to be ascertained.

The present study sought to address this gap. Considering that Hadlington et al. (2004; 2006) did not strictly measure the CSE in their studies, Experiment 1 of this study aimed first to replicate the left-ear disadvantage by comparing steady-state and changing-state sounds within-participants. Due to the acoustic pitch processing of irrelevant sound occurring in the right hemisphere (Fries & Swihart, 1990; Joseph, 1988; Mazzucchi et al., 1981; Poeppel et al., 2004; Zatorre et al., 1994; for a review, see Beaman et al., 2007), it was expected that the CSE would be more disruptive to serial recall performance for left-ear presentation, as opposed to right-ear presentation. We predicted that the CSE would be greater for changing-state sequences presented to the left ear/right hemisphere than changing-state sequences presented to the right ear/left hemisphere. To enable a comparison between the current study and that of dichotic listening studies, a condition in which steady- and changing-state sequences were presented to both ears was also deployed (Hadlington et al., 2004; 2006; cf. Sörqvist et al., 2010).

If the left hemisphere, as compared with the right hemisphere, is less affected by changing-state sequences, then variations in metacognitive monitoring may be observed depending on the ear of input of changing-state sequences. Therefore, participants might be more, or less, aware of the disruption produced by changing-state sequences depending on the hemispheric demands imposed by the focal task. To preview, in Experiment 2, we examined participants' metacognitive awareness of the differential effects of the lateralised auditory distractor sequences.

Method

Participants

Eighty adults (50 women, 30 men, mean age = 23.94 ± 3.77 years) were recruited via Prolific (https://prolific.co/), an online crowdsourcing platform for behavioural research that has been shown to generate high-quality data (Peer et al., 2017). To control for potential confounds, the following pre-screening filters were applied: autism spectrum conditions, language-related disorders, literacy difficulties, head injury, knockout history, long-term health condition or disability, ongoing mental health condition, daily impact of mental illness, access to mental health support in the last 12 months, and mild cognitive impairment or dementia. Additional eligibility criteria included self-report of normal or corrected-to-normal vision, no hearing difficulties, 18–30 years of age, born and living in the UK, English as first language, and from monolingual/monocultural background. Lastly, to ensure high quality of data, the study was restricted to individuals with a minimum approval rate of 90% on Prolific.

Since handedness can produce an attentional bias (Voyer & Flight, 2001), we only recruited participants that self-reported being right-handed, and this was verified with the administration of the Edinburgh Handedness Inventory (Oldfield, 1971).

All participants were compensated for their time at the standard payment rate recommended (£7.50 per hour of participation). A post-hoc power simulation was conducted using the PANGEA App (https://jakewestfall.shinyapps.io/pangea/) developed by Westfall (2015). This indicated that the sample size used was sufficient to achieve a minimum of 80% power with $\alpha = .05$ for detecting the effects of interest, provided that these effects correspond to an effect size *d* of at least 0.35. Ethical approval for the study was granted by the Science Ethics Committee at the University of Central Lancashire.

Design

A 2 (Distractor Type: Steady-State, Changing-State) × 3 (Auditory Location: Left Ear, Right Ear, Both Ears) within-participants design was used, with serial recall performance as the dependent variable. There were 80 trials divided into four blocks, which corresponded to the three auditory locations and an additional quiet (control) condition. The sequence of presentation conditions (left ear, right ear, both ears, quiet) was counterbalanced across participants to prevent order effects. Each block except the control condition comprised 10 steady-state and 10 changing-state trials. A random combination of spoken letters was used for each of the 30 changing-state sequences, counterbalanced across participants.

Materials

Due to the COVID-19 pandemic, and to ensure participant and experimenter safety, data was collected online using methods closely following that of Elliott et al. (2022), who recently demonstrated that auditory distraction effects can be reliably obtained and studied in online settings. The present experiment was conducted using a free, open-source study builder named lab.js (https://lab.js.org/), which offers a user-friendly interface for designing browser-based research (Henninger et al., 2021). The lab.js study was subsequently integrated with Open Lab (https://open-lab.online/), a hosting service which provides a secure foundation for online data collection.

Questionnaire Measures. Firstly, a short demographic questionnaire was used to gather information about age, gender, student status, native language, handedness, vision, and hearing. Secondly, the 10-item version of the Edinburgh Handedness Inventory (Cronbach's $\alpha = 0.88$; Oldfield, 1971) was used to assess participants' degree of handedness. It comprises ten everyday tasks (e.g. writing, throwing, opening a box) that must be marked on the appropriate column (either right or left) with a "+" if the hand preference is weak, "++" if the preference is strong, or "+" on both columns if there is no preference. A laterality quotient is then calculated based on the number of "+" marked on the left and right sides respectively, ranging from −100 (pure left-hander) to +100 (pure right-hander). Lastly, a post-experiment questionnaire developed by Elliott et al. (2022) was used to provide insight into participants' general motivation and compliance with task instructions.

Headphone Check Task. Given the online nature of the research, a screening test devised by Woods et al. (2017) was used to filter out participants who were listening over loudspeakers despite being instructed to wear headphones. The task consisted of six trials of three tones each, where the level of one tone was decreased by 6 dB, and another one was attenuated when presented over loudspeakers but not through headphones. Participants had to determine which of the three tones within each sequence was the quietest, and respond correctly on at least 5 of the 6 trials. After 5 attempts, those who were unable to pass the test were told their system did not provide the audio fidelity needed to complete the study, and therefore they would not be able to proceed.

Ear of Presentation Check Task. To ensure that participants were wearing headphones correctly, six trials of three sounds (white noise) each were presented to each ear in turn. Participants had to judge which of the three sounds within each sequence was presented to the right or the left ear, and were given 5 attempts to pass the screening test.

Irrelevant Sound Paradigm. This task involved the presentation of visual stimuli (i.e. digits) while irrelevant speech (i.e. steady-state and changing-state sequences) was played, with the ensuing requirement for strict serial recall.

Memory Lists. The to-be-remembered sequences comprised eight digits drawn from the set 1-9, with the restrictions that the lists did not begin with the number 1 and there were no descending or ascending runs of more than two numbers. The digits were visually presented in the centre of the screen, in black 72-point *Arial* font on a white background. They were displayed one-by-one, with a duration of 800 milliseconds and an inter-stimulus interval of 200 milliseconds.

Distractor Sequences. Using the first 18 letters of the English alphabet, 18 steady-state and 30 changing-state sequences were constructed. All letters were individually recorded via the Alexa Voice Service on an Amazon Echo device. They were then amplified by 20 dB to increase their volume and edited to last 250 milliseconds using the "Change Tempo" function in Audacity ® (https://www.audacityteam.org/). Additionally, their pitch was shifted down by three semitones to disguise Alexa's voice. The steady-state sequences consisted of a single letter repeated 18 times (e.g. N-N-N-N-N …), whereas the changing-state sequences consisted of a unique combination of 18 letters in random order (e.g. N-D-R-F-I …), with the constraint that each letter only appeared once and similar-sounding letters (e.g. M and N) were not presented consecutively. All letters were separated by an inter-stimulus interval of 206 milliseconds so that each sequence would last 8 s, and the onset of the first sound coincided with the onset of the first visual item.

Procedure

Participants first read an information sheet to understand what the study would entail and were requested to provide informed consent to be involved in the research. They then filled out a short demographic questionnaire, and were subsequently asked to minimise any distractions in their environment and wear headphones throughout the entire experiment. To ensure compliance with these instructions, participants were required to calibrate the volume of their device and pass the headphone and ear of presentation screening tasks. Following this, they completed the Edinburgh Handedness Inventory and were given three practice trials to familiarise themselves with the response interface. Once participants completed this short practice session, they commenced the main experiment. Auditory and visual stimuli were presented synchronously, and participants were told to ignore all sounds played over their headphones. In each trial, the numbers 1–9 were displayed on the screen after the final to-be-recalled item, and participants were prompted to click on eight of the digits in order of appearance. Immediately after the presentation of each list, participants were asked to recall the items in forward order and could not replace previous entries to correct their responses. Once the last number had been selected, participants could initiate the next trial by clicking on the "Continue" button. No performance-related feedback was provided on the recall accuracy. After finishing all 80 experimental trials, an additional audio check required participants to type in the last letter they heard ("A", "C", "L" or "N") to ensure they were still wearing headphones. Following this, participants completed the post-experiment questionnaire. Lastly, they were fully debriefed and thanked for their participation. At the bottom of the page, participants were required to confirm they were willing to submit their final responses. The study lasted approximately 35 min.

Results

For all analyses performed in this study, Cohen's *d* was reported as a measure of effect size following Cohen's (1988) conventions, along with 95% confidence intervals (CI). Bayes factors (BF_{01}/BF_{10}) were also computed for all pairwise comparisons to quantify the evidence for or against the existence of an effect. Only digits recalled in their original serial position were scored as correct, and the responses to the practice trials were excluded. Figure 1 depicts the proportion of correct responses, aggregated over serial positions, in the steady-state and changing-state trials across the three auditory locations. Serial recall performance was lower for changing-state compared to steady-state trials. The disruptive impact of changing-state sound presented to the right ear and both ears seemed comparable in magnitude. However, the disruption produced by changing-state sound appeared to be greatest when presented to the left ear.

To determine whether the experimental manipulation was effective in producing a CSE, all changing-state conditions were compared against performance in the quiet (control) condition ($M = .698$, $SD = .159$ [$SE = .018$]). The presence of changing-state sound was significantly more disruptive than silence for left-ear presentation, $t(79) = -7.78$, $p < .001$, Cohen's $d = -0.87$, $BF_{10} = 3.901 \times 10^8$, right-ear presentation, $t(79) = -3.66$, $p < .001$, Cohen's $d = -0.41$, $BF_{10} = 49.188$, and both-ear presentation, *t*

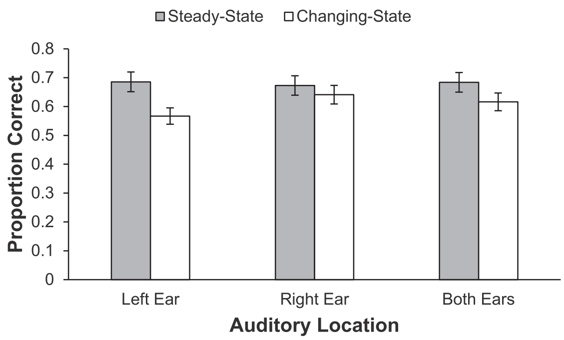

Figure 1. Mean Proportion of Items Correctly Recalled in Steady-State and Changing-State Trials as a Function of Auditory Location. Note: Error bars represent the standard error of the mean.

(79) = −5.62, $p < .001$, Cohen's $d = -0.63$, BF_{10} = 48467.095.

The data were then subjected to a 2 × 3 repeated measures Analysis of Variance (ANOVA), which revealed a significant main effect of Distractor Type, $F(1, 79) = 95.52$, $MSE = 0.01$, $p < .001$, $\eta_p^2 = .55$, suggesting that serial recall performance was significantly more disrupted by changing-state relative to steady-state trials. There was also a significant main effect of Auditory Location, $F(2, 158) = 3.49$, $MSE = 0.01$, $p = .033$, $\eta_p^2 = .04$, indicating that serial recall performance significantly varied according to ear of presentation. Lastly, the Distractor Type × Auditory Location interaction was significant, $F(2, 158) = 13.34$, $MSE = 0.01$, $p < .001$, $\eta_p^2 = .14$.

To investigate the significant interaction reported, pairwise comparisons were performed using the difference scores (steady-state minus changing-state) for each auditory location. The Holm–Bonferroni sequential method (Holm, 1979) was adopted to deal with familywise error rates for multiple tests. Essentially, the larger the number of tests undertaken, the easier it is to find a false positive and hence reject the null hypothesis, when it is in fact true. The Holm–Bonferroni method is at least as powerful as the single-step Bonferroni correction and involves rejecting one hypothesis at a time until all rejections are complete. Importantly, the Holm–Bonferroni correction keeps the inflation of Type 1 errors under control. This revealed that the magnitude of the CSE was significantly greater for left-ear compared to right-ear presentation, $p = .003$, 95% CI [0.04, 0.13], Cohen's $d = 0.54$, $BF_{10} = 282.019$, and left-ear compared to both-ear presentation, $p = .020$, 95% CI [0.01, 0.09], Cohen's $d = 0.34$, $BF_{10} = 16.250$. The magnitude of the CSE for both-ear compared to right-ear presentation did not significantly differ, $p = .075$, 95% CI [0.00, 0.07], Cohen's $d = 0.26$, $BF_{01} = 2.036$.

Discussion

Experiment 1 compared the disruptive potential of steady- and changing-state sequences presented to the left ear, right ear, or dichotically in a within-participants design. The results demonstrated that changing-state sequences were significantly more disruptive than steady-state sequences across all conditions, and that such disruption was significantly greater for left-ear compared to right-ear and dichotic presentation. These results are consistent with those of Hadlington et al. (2004; 2006) and provide an extension to their research by showing that the CSE—as indexed by comparison in performance between steady-state and changing-state trials—is enhanced following left-ear presentation. Thus, the left-ear disadvantage was only observed following the presence of acoustic fluctuations in the to-be-ignored sound which, coupled with the demand for serial rehearsal by the primary task, dictated disruption (Hadlington et al., 2006; Hughes, 2014). The findings of Experiment 1 add to the body of evidence for the right hemisphere's role in the involuntary processing of acoustic variation, triggering a marked vulnerability to auditory distraction by changing-state information (Beaman et al., 2007; Poeppel et al., 2004).

One perspective on the increased magnitude of the CSE when sequences are presented to the left ear compared to both ears is that it represents a relatively purer index of the changing-state effect and interference-by-process (Hadlington et al., 2006). On this view, monaural left ear presentation activates a contralateral pathway that suppresses one ipsilateral inhibitory pathway, whereas binaural stimulation produces inhibition in two ipsilateral pathways (Yvert et al., 1998). Irrelevant information thus flows more freely with monaural left-ear presentation but is restricted for binaural presentation. Consequently, the obligatory perception (and seriation) of changing-state sequences with left-ear presentation can flow into, and conflict with, the deliberate vocal-motoric seriation process within the right hemisphere. From the view of the duplex-mechanism account, the left-ear disadvantage—which is observed only with tasks that require seriation (Hadlington et al., 2006)—may be the manifestation of an intensified interference-by-process in the right hemisphere.

On the assumption that the enhanced CSE for left-ear as compared with dichotic presentation is the result of a relatively process-pure interference-by-process (Hadlington et al., 2004), and the perceptual streaming process driving the effect is outside conscious awareness (cf. Bell et al., 2021), the duplex-mechanism account might be taken to predict that participants should be metacognitively unaware of the left-ear disadvantage. According to the unitary account, which posits that the CSE represents attentional capture, one might expect metacognitive awareness of the greater magnitude of the CSE when presented to the left ear, relative to the right ear or dichotic presentation. This is because participants should have some metacognitive awareness of the extent to which the binaural and monoaural auditory sequences draw their focus of attention away from the serial recall task (cf. Bell et al., 2021).

Experiment 2

The purpose of Experiment 2 was, firstly, to replicate the left-ear disadvantage for the presentation of changing-state sound observed in Experiment 1, and secondly, to determine whether participants are aware of the extent to which changing-state distractors impair their cognitive performance, particularly when presented to the left ear. To investigate conscious awareness, two different types of metacognitive judgements were collected. First, prior to the experiment, we presented participants with steady-state and changing-state sequences monaurally to the left ear, right ear, and binaurally and asked them to prospectively judge how disruptive or beneficial the sequences would be in the context of the visual-verbal serial recall task. Second, trial-by-trial metacognitive monitoring judgements were collected (cf. Kattner & Bryce, 2022), whereby participants were asked if the auditory sequence on the previous trial disrupted or benefitted their performance. In line with the unitary attentional model (Bell et al., 2021), we predicted that participants should be consciously aware of the differential disruption produced by changing- as compared with steady-state sequences, and differences in the magnitude of this CSE as a function of ear of presentation (left-ear vs. right-ear vs. both ears [dichotic]). From the standpoint of the duplex-mechanism account, however, we proposed that participants may be unaware of the greater disruption produced by changing- against steady-state sequences and unaware of any differences in the magnitude of the CSE following left-ear against right-ear and dichotic presentations of sound.

Method

Participants

Seventy-nine adults (51 women, 28 men, mean age = 29.08 ± 3.77 years) who met the same inclusion/exclusion criteria described in Experiment 1 were recruited via Prolific. The post-hoc power simulation for Experiment 1, conducted using the PANGEA App (https://jakewestfall.shinyapps.io/pangea/) developed by Westfall (2015), indicated that the sample size used was sufficient to achieve a minimum of 80% power with $\alpha = .05$ for detecting the effects of interest, provided that these effects correspond to an effect size d of at least 0.35. The left-ear disadvantage observed in Experiment 1 corresponded to an effect size d of 0.54, confirming that the selected sample size was appropriate. Ethical approval for the study was granted by the Science Ethics Committee at the University of Central Lancashire.

Design

For the serial recall component of the experiment, the same design as in Experiment 1 was used. For the metacognition component, a 2 (Distractor Type: Steady-State, Changing-State) × 3 (Auditory Location: Left Ear, Right Ear, Both Ears) within-participants design was used, with subjective ratings as the dependent variable. The same counterbalancing as in Experiment 1 was followed.

Materials

The materials were identical to those used in Experiment 1, with the addition of a sliding scale ranging from −100 ("Very disruptive") to 100 ("Very beneficial") for prospective and retrospective judgement answers. Both the endpoints and intermediate points of the scale were labelled as this has been demonstrated to aid participants' understanding of the meaning of the scale, hence decreasing the variability in interpretation across respondents (Bell et al., 2021; Maitland, 2009).

Procedure

The same procedure as in Experiment 1 was followed, with the addition of a metacognitive judgements task before beginning the main experiment, and after each experimental trial. For the prospective judgements task, participants were presented with six different types of auditory sequences (changing-state and steady-state sound presented to the left ear, right ear, and both ears), and were asked to imagine hearing them during the serial recall task to appraise the effect that each one would have on their performance. The following instructions were provided: "Next, you will listen to six types of sound sequence. For each sound sequence, imagine hearing it during the memory task that you have just done. When the sound finishes, please indicate how disruptive or beneficial the sound would be for the memory task you have just done". A sliding scale (Figure 2) was displayed at the top of the screen, which participants used to indicate whether the sequences would have a disruptive, beneficial, or no effect on the memory task. For the retrospective judgements task, participants were asked how disruptive or beneficial the sound was on each experimental trial and used the same slider scale as that for prospective judgements, this time to indicate the score they felt best matched their experience of disruption.

Results

Serial recall performance (objective sound effects)

Only digits recalled in their exact serial position were scored as correct, and the responses to the practice trials were excluded. Figure 3 depicts the proportion of correct responses, aggregated over serial positions, in the steady-state and changing-state trials across the three auditory locations. Serial recall performance was lower for changing-state compared to steady-state trials. The disruptive impact of changing-state sound seemed greater when presented to both ears compared to the right ear, and the disruption appeared to be greatest when presented to the left ear.

The data were subjected to a 2 × 3 repeated measures ANOVA, which revealed a significant main effect of Distractor Type, $F(1, 78) = 68.89$, $MSE = 0.01$, $p < .001$, $\eta_p^2 = .47$, suggesting that serial recall performance was significantly more disrupted by changing-state relative to steady-state trials. The Distractor Type × Auditory Location interaction was also significant, $F(2, 156) = 16.44$, $MSE = 0.01$, $p < .001$, $\eta_p^2 = .17$. However, the main effect of Auditory Location was non-significant, $F(2, 156) = 1.75$, $MSE = 0.01$, $p = .178$, $\eta_p^2 = .04$.

To investigate the significant interaction reported, pairwise comparisons were performed using the difference scores (steady-state minus changing-state) for each auditory location. As for Experiment 1, the Holm–Bonferroni sequential method (Holm, 1979) was adopted. This revealed that the magnitude of the CSE was significantly greater for left-ear compared to right-ear presentation, $p = .003$, 95% CI [0.05, 0.13], Cohen's $d = 0.65$, $BF_{10} = 510.247$, and left-ear compared to both-ear presentation, $p = .012$, 95% CI [0.01, 0.08], Cohen's $d = 0.36$, $BF_{10} = 1.137$. The magnitude of the CSE was also significantly greater for both-ear compared to right-ear presentation, $p = .039$, 95% CI [0.00, 0.08], Cohen's $d = 0.29$, $BF_{10} = 1.843$.

Prospective metacognitive judgements

On average, steady-state and changing-state sounds across all auditory locations were associated with negative prospective judgements (Figure 4), suggesting that participants anticipated a disruptive rather than beneficial effect of irrelevant sound on cognitive performance. The main effect of Distractor Type was significant, $F(1, 78) = 96.46$, $MSE = 774.27$, $p < .001$, $\eta_p^2 = .55$, indicating that changing-state distractors were predicted to be more disruptive than steady-state distractors. However, the main effect of Auditory Location was non-significant, $F(1.78, 139) = 2.65$, $MSE = 265.81$, $p = .081$, $\eta_p^2 = .03$. Similarly, the Distractor Type × Auditory Location interaction was non-significant, $F(1.94, 151.23) = 1.71$, $MSE = 201.47$, $p = .186$, $\eta_p^2 = .02$. The Bayes factor was calculated using the R package "BayesFactor" with the default noninformative prior settings (Morey et al., 2018). The results indicated that our data was 9.12 times ($BF_{01} = 9.12$) more likely under the model that included only the main effects of Distractor Type and Auditory Location, than under the more complex model that also included the interaction term of these two factors.

Retrospective (trial-by-trial) metacognitive judgements

On average, steady-state and changing-state sounds across all auditory locations were associated with negative retrospective judgements (Figure 5), indicating that participants rated irrelevant sound as having a disruptive rather than beneficial effect on serial recall performance. The main effect of Distractor Type was significant, $F(1, 78) = 45.39$, $MSE = 238.74$, $p < .001$, $\eta_p^2 = .37$, suggesting that changing-state distractors were rated as more disruptive than steady-state distractors. The main effect of Auditory Location was also significant, $F(1.81,$

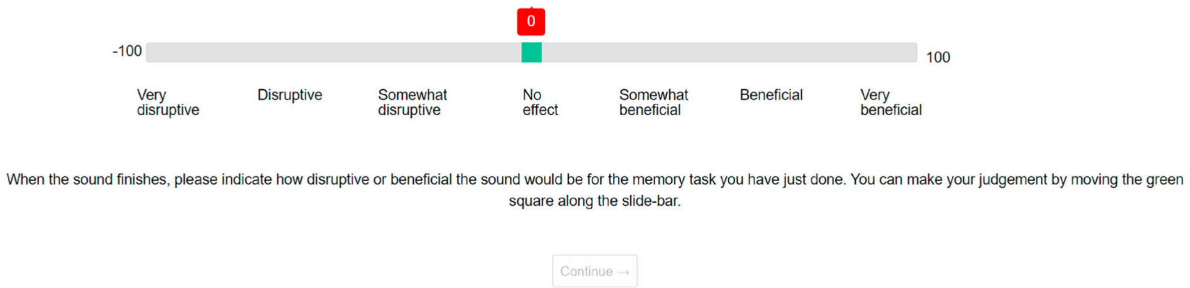

Figure 2. Rating Scale for Judging the Effects of the Different Auditory Distractors.

141.52) = 4.27, *MSE* = 165.40, $p = .019$, $\eta_p^2 = .05$, indicating that retrospective judgements varied according to ear of presentation. However, the Distractor Type × Auditory Location interaction was non-significant, $F(1.89, 147.59) = 2.84$, *MSE* = 48.35, $p = .065$, $\eta_p^2 = .04$. The Bayes factor was calculated using the R package "BayesFactor" with the default noninformative prior settings (Morey et al., 2018). The results indicated that our data was 8.91 times ($BF_{01} = 8.91$) more likely under the model that included only the main effects of Distractor Type and Auditory Location, than under the more complex model that also included the interaction term of these two factors.

To explore the significant main effect of Auditory Location, pairwise comparisons with Holm–Bonferroni adjustment were performed. This revealed that participants rated sound sequences presented to both ears as significantly more disruptive than sound sequences presented to the right ear, $p = .015$, 95% CI [0.90, 6.47], Cohen's $d = 0.36$, $BF_{10} = 14.345$. On the other hand, no significant differences were found in metacognitive judgements of sound sequences presented to the left ear and right ear, $p = 1.000$, 95% CI [−4.00, 3.15], Cohen's $d = -0.03$, $BF_{01} = 7.744$, or to the left ear and both ears, $p = .202$, 95% CI [−0.43, 6.94], Cohen's $d = 0.24$, $BF_{01} = 0.894$.

Exploratory correlational analyses

Preliminary correlations were calculated to determine whether participants who reported being negatively affected by the distractor sequences truly exhibited a decline in serial recall performance when exposed to background sound during digit memorisation. Specifically, we investigated the relationship between the objective impact of changing-state auditory distractors (represented by the difference in the average number of digits recalled per trial between the steady-state and changing-state conditions) and the corresponding prospective and retrospective judgements of their disruptive potential. This revealed a significant, moderate, positive correlation between the objective effects of changing-state sequences presented to the left ear and participants' retrospective judgements of their disruptive potential, $r(79) = .359$, $p < .001$. There was also a significant, moderate, positive correlation between the objective effects of changing-state sequences presented to the right

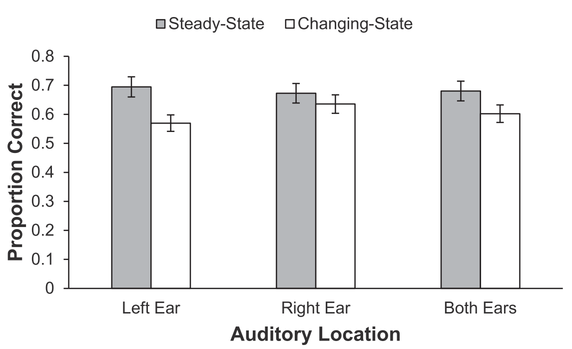

Figure 3. Mean Proportion of Items Correctly Recalled in Steady-State and Changing-State Trials as a Function of Auditory Location. Note: Error bars represent the standard error of the mean.

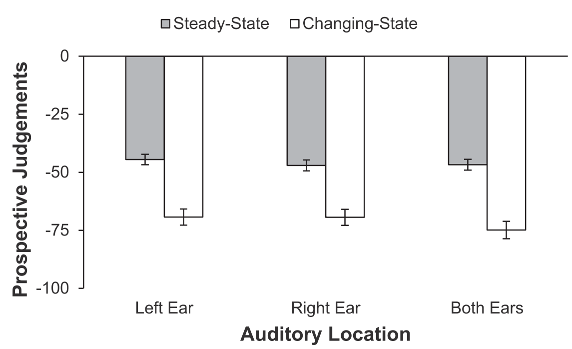

Figure 4. Mean Prospective Metacognitive Judgements of Steady-State and Changing-State Sequences as a Function of Auditory Location. Note: Error bars represent the standard error of the mean.

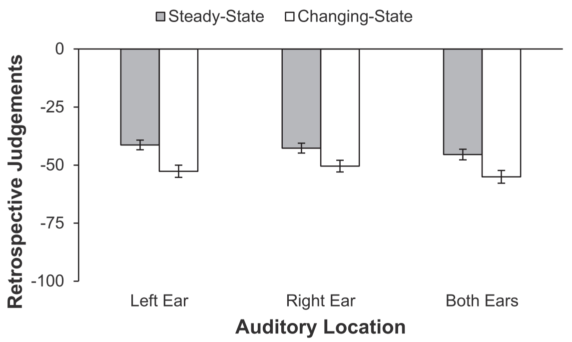

Figure 5. Mean Retrospective Metacognitive Judgements of Steady-State and Changing-State Sequences as a Function of Auditory Location. Note: Error bars represent the standard error of the mean.

ear and participants' retrospective judgements of their disruptive potential, $r(79) = .363$, $p < .001$. However, the correlation between the objective effects of changing-state sequences presented to the both ears and participants' retrospective judgements of their disruptive potential was non-significant, $r(79) = .198$, $p = .080$. On the other hand, there were no significant correlations between the objective effects of changing-state sequences presented to the left ear ($r(79) = .093$, $p = .417$), right ear ($r(79) = .054$, $p = .637$), or both ears ($r(79) = .188$, $p = .096$) and participants' prospective judgements of their disruptive potential.

Monitoring accuracy

To determine how well participants' subjective perception of their performance tallied with their objective performance, monitoring accuracy was calculated. Using the R package "rococo" (Bodenhofer et al., 2013; Bodenhofer & Klawonn, 2008), metacognitive monitoring accuracy was determined by computing robust γ-rank correlation coefficients between recall accuracy and performance judgements for each participant in each experimental condition (Kattner & Bryce, 2022). A 2 × 3 repeated measures ANOVA on monitoring accuracy (γ correlations) revealed no significant main effect of Distractor Type, $F(1, 78) = 3.15$, $MSE = 0.09$, $p = .080$, $\eta_p^2 = .04$. The trend towards a main effect of Distractor Type indicated a tendency for participants' subjective perception of their performance to more closely match their objective performance in the steady-state ($M = .35$, $SE = .023$, 95% CI [0.30, 0.40]) as compared with the changing-state ($M = .30$, $SE = .025$, 95% CI [0.25, 0.35]) sound conditions. The main effect of Auditory Location was non-significant, $F(2, 156) = 0.46$, $MSE = 0.10$, $p = .634$, $\eta_p^2 = .01$, as was the Distractor Type × Auditory Location interaction, $F(2, 156) = 1.29$, $MSE = 0.01$, $p = .279$, $\eta_p^2 = .02$. The Bayes factor was calculated using the R package "BayesFactor" with the default noninformative prior settings (Morey et al., 2018). The results indicated that our data were 458.75 times ($BF_{01} = 458.75$) more likely under the null model that did not include any main or interaction effects, as compared with the alternative model that included the main and interaction effects.

Discussion

Experiment 2 replicated the left-ear disadvantage observed in Experiment 1: changing-state distractors were significantly more disruptive than steady-state distractors across all conditions, and such disruption was significantly greater for left-ear compared to right-ear and dichotic presentation. In addition, Experiment 2 provided insight into participants' metacognitive awareness of the impact of auditory distractors. Specifically, participants predicted changing-state sequences would be significantly more disruptive than steady-state sequences (prospective judgements) and rated changing-state sequences as being significantly more disruptive than steady-state sequences (retrospective, trial-by-trial judgements). Thus, participants demonstrated accurate perceptions of the detrimental impact of changing-state sound on their serial recall performance. This suggests that, in contrast to Kattner and Bryce's (2022) findings, the effects of task-irrelevant sound on cognition can reach individuals' conscious awareness. However, no significant differences were found in metacognitive judgements of changing-state sequences presented to the left ear versus the right ear, or to the left ear versus dichotically. This indicates that participants did not hold any preconceived notions about certain auditory locations being more disruptive than others, and they were also not aware that changing-state sequences presented to the left ear had greater disruptive potential compared to the right ear or both ears. In addition, monitoring accuracy data showed that the match between participant's subjective perception of their performance and their objective performance was better in the steady-state than the changing-state condition, suggesting that changing- as compared with steady-state distractors impair monitoring of the accuracy of the retrieved sequence.

Taken together, the metacognitive judgements paint a picture that is on the face of it inconsistent with both the duplex-mechanism account (Hughes, 2014) and the unitary account (Bell et al., 2012, 2019). On the duplex-mechanism account (e.g. Hughes, 2014), participants should not have awareness of the additional disruption produced by changing- relative to steady-state sequences, given that the seriation process applied to changing-state sequences—and which interferes with focal task serial processing—is automatic and pre-attentive (see Bell et al., 2021). In contrast, evidence for the awareness of the greater disruptive effect of changing- against steady-state distractors (i.e. the CSE)—as indicated by both the prospective and the trial-by-trial retrospective judgements—has been taken as supporting the unitary account (Bell et al., 2012, 2019; Kattner & Bryce, 2022), while undermining the duplex-mechanism account (Hughes, 2014). This is because according to the unitary account participants should be aware that changing-state sequences draw the focus of attention away from the visual task, and thus of the disruption they produce (Bell et al., 2021).

On the unitary account (Bell et al., 2021), if monoaurally presented left-ear sequences have a greater propensity to capture attention than monaurally presented right-ear and binaurally presented sequences, one might predict greater awareness of the stronger disruptive effect of changing- against steady-state sequences presented to the left ear, as compared with the right ear and both ears. However, this was not observed in the prospective or retrospective metacognitive judgements. Conversely, assuming that the CSE for left-ear presentation is a purer index of the changing-state effect and interference-by-process—driven jointly by a seriation component in the focal task and the pre-attentive serial processing of sound—that is outside awareness (e.g. Hadlington et al., 2006), the duplex-mechanism account (Hughes, 2014) argues that participants should not demonstrate greater metacognitive awareness for the differential disruption of changing- relative to steady-state sequences as a function of monaural or binaural presentation. That monitoring accuracy was poorer in the changing-state condition than in the steady-state condition could be reconciled within the unitary account (Bell et al., 2021), wherein the withdrawal of the focus of attention from the visual items may impair the mapping between the presented sequence and the retrieved sequence. However, the same results are also consistent with the duplex-mechanism account (Hughes, 2014), arising due to the loss of order information from the conflict between pre-attentive and deliberate seriation processes.

General discussion

The first aim of this study was to (re)investigate hemispheric asymmetries in auditory distraction by manipulating the spatial location of to-be-ignored sound and examining the corresponding ear disadvantages. In this regard, it was predicted that the CSE would be more disruptive for left-ear compared to right-ear and both-ear presentation. The findings of Experiment 1 supported this prediction and, through the provision of both steady- and changing-state trials in a within-participant design, extended previous research by providing a direct measure of the CSE in the context of hemispheric lateralisation (cf. Hadlington et al., 2004; 2006). Bayesian evidence strongly favoured the alternative hypothesis, highlighting the presence of differences between left-ear and right-ear presentation, as well as left-ear and both-ear presentation, of changing-state sequences on serial recall performance. This pattern of results lends credence to the right hemisphere specialisation for processing the acoustic properties of changing-state information, which transforms into a disadvantage when the task entails seriation, and the auditory stimuli must be deliberately ignored. These findings can be accommodated by an interference-by-process framework (Hughes & Marsh, 2017; Jones & Tremblay, 2000), given that the characteristics of the sound (i.e. changing-state) and the processes involved in the task (i.e. serial rehearsal) determine the magnitude of the disruption produced via left-ear presentation.

Hemispheric asymmetries in auditory distraction: process or attention?

The finding of a left-ear disadvantage for the presence of changing-state sequences in Experiments 1 and 2 coheres with the work of Hadlington et al. (2004, 2006). Moreover, the findings support the notion that the right hemisphere plays a special role when the pre-attentive and involuntary processing of order information within sound streams disrupts the deliberate order processing of the to-be-remembered items via serial rehearsal. Our results are consistent with the notion that the CSE obtained with left-ear presentation is a purer changing-state effect than that obtained from right-ear or dichotic presentation. This is because, with binaural presentation, two ipsilateral inhibitory pathways are expected to inhibit the flow of irrelevant speech information relative to monoaural left-ear presentation. For monoaural left-ear presentation, the presence of only one ipsilateral inhibitory pathway means that the irrelevant information flows relatively freely into the right hemisphere for processing, wherein the similar serial processing responsible for the retention of the to-be-remembered sequence is occurring, thereby yielding interference (Hadlington et al., 2004, 2006). Given that the right hemisphere-dominant processes underpinning the analysis of acoustic features are pre-attentive (Beaman et al., 2007; Poeppel et al., 2004), the lack of metacognitive awareness of the increased magnitude of the CSE with left- as compared with right-ear and dichotic presentation fits with the duplex-mechanism account (Hughes, 2014), according to which the CSE is the legacy of an automatic processing of order. In future work, it would be theoretically valuable to compare the serial recall task with a task that does not require serial order while manipulating the spatial location of distractor presentation and recording metacognitive judgements. Although we did not manipulate task characteristics in the current study, it should be noted that when the focal task requires semantic processing, a right-ear disadvantage is found for the between-sequence semantic similarity effect: the finding that to-be-ignored category exemplars drawn from the same, as compared with a different, semantic category as target exemplars produce greater disruption to target recall (Sörqvist et al., 2010). This finding gels with the idea that the left hemisphere plays a dominant role in the semantic processing of speech sounds (e.g. Beaman et al., 2007; Scott et al., 2009; Zahn et al., 2000) and the occurrence of interhemispheric inhibition of speech presented to the left ear (Bloom & Hynd, 2005; Clarke et al., 1993; Westerhausen & Hugdahl, 2008). Collectively, the observation of these left- and right- ear disadvantages depending on the nature of the focal task and characteristics of the sound supports the interference-by-process component of the duplex-mechanism account (Hughes, 2014) and the structural basis of hemispheric differences (Kimura, 1961a, b).

One alternative to the structural account of the right ear advantage, however, is a theoretical perspective based on attention (Kinsbourne, 1970; Voyer & Flight, 2001). On this view, the left hemisphere is "primed" to accept greater information from the right side of the auditory space when verbal information is presented to the right ear (Kinsbourne, 1970; Voyer & Flight, 2001). This increases participants' awareness of the right side of both the auditory and visual spaces. In the context of dichotic listening tasks (e.g. Kinsbourne, 1970; Querné et al., 2000), this results in increased accuracy for information presented to the right. One possibility, then, is that participants become more "attentionally aware" of changing-state verbal information presented to the left ear as a result of priming, which in turn increases the disruptive power of the sequences as compared with dichotic presentation due to attentional diversion. However, one problem with such an attentional account is that one might expect metacognitive awareness judgements, at least retrospective ones, to be sensitive to the additional disruption produced by left-ear against right-ear and dichotic presentation. The insensitivity of metacognitive judgements to the left-ear disadvantage may reflect either an unawareness of the additional disruption (consistent with the duplex-mechanism account; Hughes, 2014), or a sensitivity only to the CSE, but not its magnitude.

Are metacognitive judgements diagnostic of distraction mechanisms?

From their prospective metacognitive judgements, Bell et al. (2021) demonstrated that participants' metacognitive beliefs about the disruptive impact of deviant and changing-state sequences were accurate. That is, without and/or before actually experiencing disruption, participants believed that deviant and changing-state sequences, as compared with steady-state sequences, would be disruptive. However, this does not in itself provide any insight into whether participants were aware of the disruption produced by changing-state sequences, or any less aware of the disruption produced by changing-relative to steady-state sequences. Notably, a similar criticism applies to our Experiment 2, wherein changing-state distractors were predicted to be more disruptive than steady-state distractors regardless of their spatial presentation. Further, the retrospective judgements of the disruption actually produced in Bell et al.'s (2021) study mirrored those of the prospective judgements, given that deviant and changing-state sequences were rated as more disruptive than steady-state sequences. Therefore, the retrospective metacognitive judgements arguably say nothing about participants' awareness of the disruption that is actually experienced because they are indistinguishable from the prospective judgements that are made prior to the experiment. Again, such a critique can be applied to our Experiment 2, for which prospective and retrospective ratings also married with judgements of greater disruption from changing- relative to steady-state distractors. However, the prospective as compared with retrospective judgements differed since, in the latter, participants judged sound sequences presented to the left ear as more disruptive than those presented to the right ear, regardless of their state, which was not observed in the objective data.

In their exploratory analyses between retrospective judgements of disruption levels and actual (i.e. objective) levels of disruption, Bell et al. (2021) reported no inter-individual correlations. This appears to undermine the view from the unitary account (Bell et al., 2021) that people are equally aware of the disruption produced by changing-state and deviant sounds. Using trial-by-trial retrospective confidence judgements, Kattner and Bryce (2022) showed that participants are aware of the disruptive effects of both deviant and changing-state against steady-state sequences, which on the face of it conflicts with the automaticity assumption of the CSE (Hughes, 2014), but is consistent with the unitary account (Bell et al., 2012).

In our exploratory correlations of Experiment 2 data, we found that our trial-by-trial retrospective judgements correlated with the actual (i.e. objective) disruption produced by changing-state sequences, both when the sequences were presented to the left ear and when they were presented to the right ear, but not when they were presented to both ears. Although this pattern would appear to undermine the duplex-mechanism account, if it is assumed that participants should not have awareness of the disruption produced by changing-state as compared with steady-state sequences, it is equally inconsistent with the unitary account (Bell et al., 2021). On this account, it is difficult to interpret why participants would be aware of the disruption produced by changing- against steady-state distractors (i.e. the CSE) when it is strongest in magnitude (i.e. for left-ear presentation) and weakest in magnitude (i.e. for right-ear presentation), but not intermediate in magnitude (i.e. with dichotic presentation that is typical of most studies). This failure to find an inter-individual correlation between retrospective judgements and observed disruption with dichotic presentation does echo the findings of Bell et al. (2021).

Our study, like that of Kattner and Bryce (2022), demonstrated that participants were sensitive to trial-by-trial variations in their performance as a function of type of distractor (but not of ear of presentation; see Experiment 2). However, whereas Kattner and Bryce (2022) reported that metacognitive monitoring accuracy was unaffected by distractor type, our Experiment 2 showed a trend for monitoring accuracy to be poorer for changing-state as compared with steady-state distractors. Notwithstanding the difference in metacognitive monitoring accuracy falling short of significance between changing- and steady-state conditions, a poorer mapping of the subjective perception of disruption and objective performance in the changing-state condition could be explained by attentional capture (Bell et al., 2021) or interference-by-process (Hughes, 2014), so is arguably not diagnostic.

Continuing the question of whether metacognitive judgements are diagnostic of the mechanism of distraction, one criticism that could be applied to the trial-by-trial retrospective ratings is that participants may base their "metacognitive" judgements of disruption on some internal feedback relating to how they performed on the just-presented trial (perhaps via monitoring positional information, or the strength of memory traces; see Nelson & Narens, 1990), and then make a mental note of the type of auditory sequence they had just encountered. That is, participants may lack direct awareness about what is causing their performance variations. Therefore, the metacognitive awareness of the differential disruption produced by changing- and steady-state sequences in Experiment 2 may not necessarily reflect (metacognitive) awareness of "online" disruption during list memorisation.

Another potential problem with trial-by-trial retrospective judgements is that they might alter processing of the focal task, perhaps by inadvertently drawing attention towards the irrelevant sounds. Indeed, the act of reflecting on and evaluating their performance on each trial might cause participants to engage more actively with the auditory distractors, rather than remaining focused on the primary task. Therefore, although attempts are made to mitigate this potential confound by providing participants with explicit instructions to ignore the auditory stimuli, it is important to acknowledge that variations in individual participant adherence may persist. Metacognitive judgements might also alter task processing by prompting a more effective strategy, a shift in task-goals, or a competition for resources to arise between the focal task and providing the monitoring judgement (Mitchum et al., 2016). However, there is mixed evidence for such reactivity to monitoring judgements (see Double & Birney, 2019), and such reactive effects are questionable in Experiment 2 since performance under steady-state and changing-state conditions strongly resembled Experiment 1, wherein no metacognitive ratings were recorded.

At the conceptual level, one might call into question a key assumption regarding the ability to tease apart the duplex-mechanism and unitary accounts—whether being consciously aware of the disruptive effects of a stimulus precludes the existence of automatic processes that operate beyond conscious awareness. It is possible that participants are consciously aware of the disruptive nature of changing- over steady-state sounds, but this does not rule out the co-existence of automatic, pre-attentive processes that occur outside their conscious awareness which contribute to the changing-state effect. Similarly, participants might not have direct access to the processes that produce auditory distraction and instead rely on heuristic cognitive judgements about the distracting effects of sound. For example, Bell et al. (2023) reported that their participants judged music sequences played backwards to be more disruptive than those presented in a forward (i.e. normal) direction. Objectively, forwards- and backwards-played sequences were equally disruptive of visual-verbal serial recall. Bell et al. (2023) concluded that their results undermine the notion of direct access, and instead support the view that participants rely on feelings of processing fluency to make heuristic metacognitive judgements about the disruption produced by sounds (see also, Bell et al., 2024). Importantly, these heuristics can result in systematic and predictable errors leading to the genesis of metacognitive illusions—such as believing that some forms of music are beneficial, or less detrimental, to ongoing task performance than others (Bell et al., 2023).

In relation to conscious awareness, the informativeness of metacognitive judgements in characterising mechanisms of auditory distraction rests upon the idea that metacognitive processes obligatorily evoke awareness (e.g. Bell et al., 2021). This is a contentious issue since there is a body of empirical evidence suggesting that metacognitive processes can be engaged in the absence of awareness (Kentridge & Heywood, 2000; Polyanskaya, 2023; Spehn & Reder, 2000). If metacognitive processes are indeed engaged without awareness, then this undermines the claim that metacognitive awareness of the CSE (i.e. that changing-state sounds are more disruptive than steady-state sounds) rules out the notion that it arises from automatic processes. Furthermore, participants may be metacognitively aware of the detrimental impact of changing-state compared to steady-state sound, but not necessarily consciously aware of this.

In sum, more empirical work is required to determine whether the metacognitive judgements deployed here (Experiment 2) and elsewhere (Bell et al., 2021; Kattner & Bryce, 2022) adequately capture awareness of performance disruption produced by auditory sequences and, in doing so, can tease apart the duplex-mechanism (Hughes, 2014) and unitary (Bell et al., 2012, p. 2012) accounts.

Limitations

The current study is subject to certain limitations. Firstly, while auditory distraction research can successfully be conducted online (Elliott et al., 2022), there are several challenges associated with it. In particular, the study may have been hampered by a lack of experimental control over the presentation of the to-be-ignored material and the characteristics of the testing environment. It is possible that some participants accessed the study using a device with poor sound quality and completed it under the influence of extraneous noise or visual distractors, which would weaken the effects under observation. Although great care was taken to ensure participant compliance with task instructions within the study, at points prior to the attention-check, participants may have turned off the sound or taken off their headphones. Future investigations could attempt to replicate the effects observed in Experiments 1 and 2 with face-to-face methods to determine whether, and to what extent, they differ from those obtained in online settings.

Conclusion

Given the omnipresence of sound, demanding activities are often undertaken in the face of task-irrelevant auditory stimuli, leading to distraction of goal-oriented performance. This study established that changing-state sequences were particularly disruptive regardless of their increased disruption when presented to the left ear. Identifying the differential power of auditory distractors to disrupt performance can thus guide the design of work and learning environments with optimal sound distribution, as well as the development of effective noise reduction measures that shield individuals against the detrimental impact of task-irrelevant sound (e.g. Vachon et al., 2017). Moreover, exploring how the spatial location of the sources of distraction affects human performance can shed light on the differential processing of auditory stimuli by the left and right hemispheres (Clark & Sörqvist, 2012). While an understanding of participants' metacognitive awareness of the objective disruption produced by a distractor sequence is important for self- or other-imposed decisions about their working environments, it is perhaps too early to tell whether metacognitive judgements shed light on the mechanisms underpinning auditory distraction in the context of short-term memory.

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Data availability statement

The data that support the findings of this study may be found at https://doi.org/10.6084/m9.figshare.23605521.

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