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Irrelevant changing-state vibrotactile stimuli disrupt verbal serial recall: implications for theories of interference in short-term memory

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ABSTRACT

What causes interference in short-term memory? We report the novel finding that immediate memory for visually-presented verbal items is sensitive to disruption from task-irrelevant vibrotactile stimuli. Specifically, short-term memory for a visual sequence is disrupted by a concurrently presented sequence of vibrations, but only when the vibrotactile sequence entails change (when the sequence "jumps" between the two hands). The impact on visual-verbal serial recall was similar in magnitude to that for auditory stimuli (Experiment 1). Performance of the missing item task, requiring recall of item-identity rather than item-order, was unaffected by changing-state vibrotactile stimuli (Experiment 2), as with changing-state auditory stimuli. Moreover, the predictability of the changing-state sequence did not modulate the magnitude of the effect, arguing against an attention-capture conceptualisation (Experiment 3). Results support the view that interference in short-term memory is produced by conflict between incompatible, amodal serial-ordering processes (interference-by-process) rather than interference between similar representational codes (interference-by-content).

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A central debate in contemporary cognitive psychology concerns the mechanisms underpinning interference in short-term memory (Endress & Szilárd, 2017; Oberauer et al., 2018). According to one standpoint, the key determinant of interference in memory is stimulus similarity/overlap: Interference occurs when memory representations overwrite similar memory representations (Baddeley, 2012; Hanley & Bakopoulou, 2003; Henson et al., 2003; Neath, 2000; Oberauer, 2009; Oberauer & Kliegl, 2006; Page & Norris, 2003; Vergauwe et al., 2010). The present research is rooted within an alternative theoretical framework positing that interference arises instead from the conflict between similar processes being engaged concurrently (e.g. seriation; Jones & Macken, 1993; Jones & Tremblay, 2000; Hughes et al., 2005, 2007; Marsh et al., 2009; Sörqvist, 2010). In the present study, we examined the possibility of extending a well-established auditory distraction phenomenon – the changing-state effect (Jones et al., 1992) – to the tactile domain to tease apart interference-by-content and interference-by-process accounts.

Irrelevant sound distraction

The ability to reproduce a visually-presented sequence of verbal items is invariably impaired when a to-be-ignored auditory sequence is presented concurrently, in comparison with when

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the visual sequence is presented in silence (Bell et al., 2012; Hughes et al., 2005, 2007; Jones & Macken, 1993; Labonté et al., 2021; LeCompte et al., 1997; Miles et al., 1991; Röer et al., 2020; Salamé & Baddeley, 1982; Sörqvist, 2010; Tremblay & Jones, 1998; Vachon et al., 2020). This "irrelevant speech effect" (Colle & Welsh, 1976) or "irrelevant sound effect" (since qualitatively similar effects are found with non-speech sounds; Beaman & Jones, 1997) has been studied extensively (Hughes, 2014; Jones et al., 2010) and is a model case for the understanding of cross-modal interference within short-term memory. Similar effects of disruption of short-term memory by irrelevant sound are also found when the to-be-recalled items are presented in the auditory domain (Schlittmeier et al., 2006). Thus, the irrelevant sound paradigm can be used to study both cross-modal and within-modal interference in short-term memory and inform theories of interference in short-term memory generally.

Explanations of the irrelevant sound effect: interference-by-content vs. interference-by-process

Proposed explanations of the irrelevant sound effect can be classified into two broad classes. One is an interference-by-content class of explanation, which assumes that interference in the irrelevant sound effect arises because of a similarity between the contents of the to-be-recalled items and the to-be-ignored (sound) items. The other is the interference-by-process class of explanation, according to which the interference arises due to a clash between incompatible processes. The distinction between interference-by-content and the interference-by-process accounts is also accompanied by a distinction between structuralistic versus functionalistic views of human cognition. Some (but not all) interference-by-content explanations assume that the human cognitive system comprises separable stores or cognitive structures. One such explanation is the phonological loop model (Baddeley, 2012; Baddeley & Hitch, 2019) which assumes that the human cognitive system comprises functionally separable stores in which information is maintained. The interference-by-process accounts of the irrelevant sound effect, in turn, make no assumption about cognitive structures but instead assume that general-purpose motoric and perceptual processes are involved in producing the disruption (Hughes et al., 2016).

Interference-by-content

The phonological loop account of the irrelevant sound effect assumes that items of visual and auditory origin gain access to the same storage space in short-term memory. Herein interference is a function of the similarity in content between the to-be-recalled items and the to-be-ignored items within that storage-space of short-term memory (Hanley & Bakopoulou, 2003; Salamé & Baddeley, 1982). According to the Working Memory model (Salamé & Baddeley, 1982), to-be-ignored auditory items gain automatic access to a phonological short-term memory store wherein they meet visually-presented items that have reached the same store via an indirect route. These visually-presented items must first be transformed into phonological representations through a grapheme-to-phoneme conversion process prior to representation within the store. On this view, interference is a function of the phonological similarity between the background sound and the to-be-recalled items (Baddeley, 1986; Salamé & Baddeley, 1982).

A more recent implementation of an interference-by-content account (e.g. Norris et al., 2004; Page & Norris, 2003) assumes that when within the common content-defined store, interference occurs at the level of order, not item-content, representation (see also Henson et al., 2003). That is, an interference-by-(order)-process is superimposed on the similarity of content at the general level so long as the to-be-ignored and to-be-remembered material is phonological or sufficiently phonological-like (e.g. sequences of tones). On this account, once represented within the phonological store, a sequence of changing-state sounds is represented by a primacy gradient of activation. The primacy gradient of activation for these sounds commandeers attentional resources necessary to represent the order of to-be-remembered visually-presented items. Therefore, for interference to occur within this interference-by-content model, to-be-remembered and to-be-ignored material must meet at a (modality-independent) phonological/phonological-like level of representation within the cognitive system. If the to-be-ignored material cannot be represented within the phonological store (e.g. non-speech, or insufficiently speech-like, material), then neither can a primacy gradient of activation representing the sequential order of changes within that material. Hence, the primacy gradient of activation representing the to-be-recalled items will be unaffected.

Other interference-by-content accounts (Neath, 2000; Oberauer, 2009; Oberauer & Kliegl, 2006; Oberauer & Lin, 2023) do not posit a distinct short-term memory store, or at least not separate modality-specific stores. From this theoretical standpoint, interference derives from stimulus similarity/overlap generally (not just within a separate short-term memory store) which can give rise to new items overwriting the representations of older items. For example, Lange and Oberauer (2005) identify feature deletion and feature adoption as two forms of overwriting. Feature deletion occurs when a new stimulus overwrites some of the features contained in the representations of previous stimuli (Nairne, 1990), and feature adoption occurs when some of the features of new stimuli are incorporated into the representations of previously stored stimuli (Neath, 2000). Both purported processes result in poorer recall of the to-be-remembered representations.

There are hence a number of differences between the interference-by-content accounts. For example, the feature model assumes that interference arises when a feature from the irrelevant background sound is adopted into the noisy cue for the to-be-recalled items (Neath, 2000), whereas the primacy model assumes that interference arises when a secondary primacy gradient draws resources away from the main primacy gradient (Page & Norris, 2003). Yet, a common tenet of the interference-by-content views is the assumption that interference, such as that underpinning the irrelevant sound effect, is attributable to a conflict between representations in a specific memory component (Baddeley & Hitch, 2019; Hanley & Bakopoulou, 2003; Henson et al., 2003; Norris et al., 2004) or within memory generally (Neath, 2000; Oberauer, 2009; Oberauer & Greve, 2022; Oberauer & Kliegl, 2006). This view remains faithful to the view of interference whereby the extent to which items are successfully retrieved is modulated by the existence of other stimuli or events to the rate that they are similar to the target (Baddeley, 1986; McGeoch, 1942; Nairne, 1990, 2002; Neath, 2000). Interference in short-term memory on this approach is a passive side effect that results from storing similar events in memory (Oberauer & Lange, 2008; Oberauer et al., 2004; Salamé & Baddeley, 1982). For example, Norris et al. (2004) showed that irrelevant sound, presented during a retention interval between presentation and recall of a set of to-be-recalled items, had retroactive effects on the material in memory, but not when the visual to-be-recalled items were presented concurrently with articulatory suppression. The authors concluded that the irrelevant sound effect takes place in the phonological-store component of short-term memory, as the effect disappears when the articulatory-loop component is occupied (with the suppression task) during presentation of the to-be-recalled information – which then cannot gain access to the phonological short-term memory store. This assumption that the irrelevant sound effect "depends on the [to-be-remembered] information's having been encoded into the phonological store" (p. 1103) implies that disruption from irrelevant sound arises from the to-be-ignored spoken items in phonological form coexisting – hence interfering – with the to-be-recalled list items that also possess a phonological form within the store.

Evaluation of the interference-by-content approach

Several findings from the irrelevant sound paradigm are difficult to reconcile with the view that interference arises due to a similarity in content between the to-be-attended material and the to-be-ignored stimuli. First, interference also arises when the background sound has been stripped of any phonological content – such as the case with a sequence of tones (Jones & Macken, 1993; LeCompte et al., 1997; Sörqvist, 2010) or when the task requires serial recall of sequentially presented locations of dots (Jones et al., 1995). Hence, disruption does not appear to be a function of phonological similarity between the memoranda and the to-be-ignored sequence. Second, the degree of interference depends on how the to-be-recalled items are cognitively operated on, as shown by manipulations of task instructions. Instructing participants to either recall the items in serial or in free order, for example, modulates the degree of interference, even though the contents of the to-be-recalled items remains the same (Marsh et al., 2008). Interference thus appears to be a function of the motoric act of serially rehearsing the to-be-recalled items (Beaman & Jones, 1997, 1998; Hughes & Marsh, 2020; Perham et al., 2007). The crucial role of the type of cognitive operation that acts upon the to-be-recalled items is difficult to explain within an interference-by-content approach.

Distraction is also a function of the degree of perceivable change within the sound sequence (Macken et al., 2009). For example, a steady-state sound sequence that does not change (e.g. "m m m m m m m m") leaves short-term memory performance relatively unharmed, while a changing auditory sequence (e.g. "m k m k m k m k") produces disruption (Tremblay & Jones, 1998): the so-called *changing-state effect* (Jones et al., 1992). Speech may be more disruptive than non-speech sounds (LeCompte et al., 1997; Viswanathan et al., 2014), but this may be because speech is particularly rich in changing-state information and so, consistent with this, the effect of speech and non-speech are qualitatively (but not necessarily quantitatively) similar (Tremblay et al., 2000).

Of most relevance for the current research is prior work that was motivated to address the notion of the generality of interference (Jones et al., 1995). Changing-state speech as compared to steady-state speech produced greater impairment of visual-verbal and visuospatial serial recall. Although generally more errors were made in the spatial task than the verbal task (see also Vachon et al., 2017), the magnitude of disruption produced by changing-state vs. steady-state stimuli was comparable across the two tasks. These results clearly undermine the notion that interference occurs to the extent that representations are like one another. According to the Working Memory model (Salamé & Baddeley, 1982), representations of non-verbally recoded spatial locations should not interfere with the phonological representations of verbal material, as they are not represented within the same storage space. The present study uses a different approach to address fundamentally the same question using to-be-ignored stimuli that bear little resemblance to to-be-remembered items at perceptual and mnemonic levels of representation.

Interference-by-process

Taken together, previous findings from studies on the irrelevant sound effect are more consistent with an interference-by-process account of interference (Hughes et al., 2005, 2007; Jones & Tremblay, 2000; Marsh et al., 2015). On this view, the changing-state effect arises through a conflict between the ability to serially rehearse/process the to-be-recalled items and the perceptual organisation (Bregman, 1990) of the auditory input into a stream that extracts order information from the sound sequence. Therefore, interference arises due to conflict between incompatible general perceptual and motoric processes that have mnemonic consequences (Hughes, 2014; Hughes & Marsh, 2017; Jones & Macken, 1993; Marsh et al., 2009; Sörqvist, 2010). This view assumes that short-term retention is underpinned by perceptual and motor skills (Hughes et al., 2016). Therefore, there is no requirement within the human cognitive system for the phonological store and the associated loss of information through "interference" based on (phoneme) similarity and the presence of speech-like material that co-occupies the store with phonemes derived from visual items (Hughes et al., 2009;).

A distinguishing feature of the interference-by-process view is the assumption that interference depends on the transitions between items, not on item-specific attributes. While the interference-by-content view assumes that interference depends on the similarity between items and their contents (e.g. phonemes, features), the interference-by-process view assumes that interference takes place in an amodal workspace and depends on inter-item relationships. In the present paper, we make use of a novel distractor source to contribute to this debate on the causes of interference. Specifically, we ask: Is visual-verbal short-term memory disrupted by vibrotactile stimuli? If changing vibrotactile stimuli were to disrupt verbal memory, this would offer further, compelling, evidence against the interference-by-content account since vibrations, unlike phonemes (cf. Salamé & Baddeley, 1982), should not be represented by mnemonic (e.g. phonological) features.

Vibrotactile distraction

A central principle held by the interference-by-process view is the assumption that interference arises between two streams that depend on the inter-item relationship in the to-be-ignored and the to-be-recalled sequences, rather than between contents of two sources of information within a phonological store. Therefore, the distractors would not have to be represented in a speech-like form to produce disruption of verbal short-term memory. A vibrotactile sequence of distractors, for example, should also be able to produce a changing-state effect, even though such stimuli are unlikely to yield a representational code (e.g. phonological) that shares features or contents with the visual to-be-recalled items. The distracting impact of irrelevant vibrotactile stimuli has recently attracted the attention of a few researchers. While Marsja et al. (2018, 2019) investigated the effectsof auditory, vibrotactile, or combined auditory and vibrotactile (i.e. bimodal) sequences on visual-verbal and visuo-spatial serial recall, they were interested in disruption produced by a change in a regular pattern of stimulation – a deviant. Thus the authors were not concerned with whether a changing-state effect could be observed in the vibrotactile domain.

In the current paper, we test the novel hypothesis that vibrotactile stimuli can produce a changing-state effect in the context of short-term memory. The perceptual organisation principles in audition (Bregman, 1990) are also present for tactile perception (Gallace & Spence, 2011). For example, tactile stimuli that appear to have a common fate are perceived as emerging from the same source. Yet, whereas the cues involved in the grouping of auditory stimuli – in the formation of auditory objects, for example – are mainly frequency- and time-based (see Bregman, 1990), they are more somatotopic and space-based in the case of tactile information (see, Gallace & Spence, 2011). A changing-state sequence of vibrotactile input, such as a sequence of vibrations alternating between the two hands of a person, should therefore be perceptually organised into a changing-state object (as an object jumping back and forth between the two hands). Because of this, the interference-by-process account predicts that a changing-state vibrotactile input should produce more disruption to serial recall of visually-presented verbal items, as compared with a steady-state vibrotactile sequence.

Conversely, according to the interference-by-content account, there should be no difference in disruptive power between a changing-state and a steady-state vibrotactile sequence because the vibrotactile stimuli should not enter into a purported phonological store (cf. Baddeley, 1986; Norris et al., 2004; Page & Norris, 2003) or a continuous space wherein interference occurs to the rate that representations are similar to one another (Neath, 2000; Oberauer, 2009; Oberauer & Kliegl, 2006). Indeed, Bancroft and Servos (2011; see also Bancroft et al., 2013) proposed that vibrotactile stimuli are represented solely in a vibrotactile working memory as a set of feature units representing *only* frequency information. In a vibrotactile delayed match-to-sample task, they reported that judgements of whether a probe had the same or a different vibrational frequency as a target was disrupted by the presentation of a vibrotactile distractor in the delay period between the offset of the target and the onset of the probe. Moreover, when the target and distractors were of a different frequency, greater impairment was observed from a vibrotactile distractor whose frequency lay between the target and probe frequencies, than from one whose frequency lay farther from the probe frequency. Bancroft and Servos (2011) suggested that the encoding of the distractor stimulus into vibrotactile working memory caused overwriting of the previously stored representation of the target stimulus. Furthermore, they argued that if the feature overwriting results in a frequency representation that is more similar to the probe frequency (as is the case when the vibrotactile distractor has a frequency in between the target and probe), then participants should be more likely to erroneously decide that the target and probe frequencies are the same. This was the pattern that Bancroft and Servos observed in their study. Generally, the finding that vibrotactile input – either steady- or changing-state – interferes with visual-verbal short-term memory would constitute a major problem for inference-by-content classes of models.

The present study

In this paper, we report a series of experiments that explore the effects of changing-state vibrotactile sequences on short-term memory. Experiment 1 compared the impact of vibrotactile and auditory changing-state sequences on visual-verbal serial recall and found that the two types of distractors appear to have similar disruptive effects. Experiment 2 tested the effects of the same distractor sequences on the missing item task, a task that arguably requires memory of item-identity but not of item-order (e.g. Beaman & Jones, 1997), and found that both vibrotactile and auditory distractors failed to disrupt memory for item-identity, suggesting that disruption from changing-state irrelevant sequences is restricted to serial-order memory. Finally, Experiment 3 was designed to replicate the vibrotactile changing-state effect in another context that induces a serial rehearsal strategy, namely the probed order task, and to explore whether the predictability of the vibrotactile changing-state sequence modulates the magnitude of the effect, which it did not appear to.

Experiment 1

The goal of this experiment was to establish an effect of changing-state stimulation in the tactile domain. Within the traditional context of the visual-verbal serial recall task, participants had to recall the order of presentation of a series of visually-presented digits while being presented with a to-be-ignored sequence of vibrations. The sequence of vibrotactile distractors could be composed of steady-state vibrations (presented to both hands simultaneously) or changing-state vibrations (alternating from one hand to the other). A no-distractor condition served as a control condition. If, as predicted, the changing-state effect is not restricted to audition and can be extended to touch, serial recall was expected to be lower in the changing-state condition than in the steady-state conditions. To directly compare the vibrotactile changing-state effect to its well-established auditory counterpart, the experiment also included auditory distractor conditions consisting of either changing-state spoken letters (the alternation of the letters ‘a’ and ‘b’) or steady-state spoken letters (the repetition of the same letter).

Method

Participants

Thirty students participated in the experiment in exchange for a small honorarium. Using G*power (Faul et al., 2007), we performed a sensitivity analysis for the critical test of whether a changing-state effect occurs in both auditory and tactile conditions. With 30 participants and given $\alpha = .05$ and a power level of .95, and assuming a correlation between the levels of the repeated-measures variable of .50, it was possible to detect differences of size $f = 0.34$ between steady-state and changing-state conditions, which is sufficient given the typical size of the (auditory) changing-state effect reported in the literature.

Materials and apparatus

The experiment was programmed using PsychoPy (Pierce, 2007) and executed on computers running Windows 7 Enterprise.

Vibrotactile stimuli

The vibrations were delivered through a specially built device consisting of two handles built of transparent plastic tubes (diameter = 30 mm, length = 136 mm; see Figure 1). At the top of each handle, a response button was located. Inside of the tubes, a motor was used to cause vibration by spinning an eccentric mass on its rotor. The handles were controlled by a unit that was connected to a computer parallel port. To block out possible sounds from the motors, participants wore sound attenuating Vic Firth headphones. The vibration stimulus had an amplitude of 2.3 m/s^2 (r.m.s.) and a frequency of 33 Hz and was presented for 250 ms.

In the steady-state vibrotactile condition, the vibration was presented to both hands simultaneously. In the changing-state vibrotactile condition, the vibration was spatially manipulated such that only one of the handles vibrated at a time (i.e. changing between hands; see Figure 2).

Auditory stimuli

Since changing-state within the vibrotactile domain represents a simple change in state, we compared this to a condition within which the minimal requirement for the criterion of changing-state is satisfied within the auditory domain: two alternating tokens (Jones & Tremblay, 2000). For the auditory conditions then, participants received a changing-state stream comprising alternations of the letters “a” and “b” (e.g. “a b a b a b a b a”) as compared with steady-state repetition of one of the two letters (e.g. “a a a a a a a a a”; see Figure 2). The two letter tokens were recorded in a

Figure 1. Picture of the vibrotactile stimulation device.

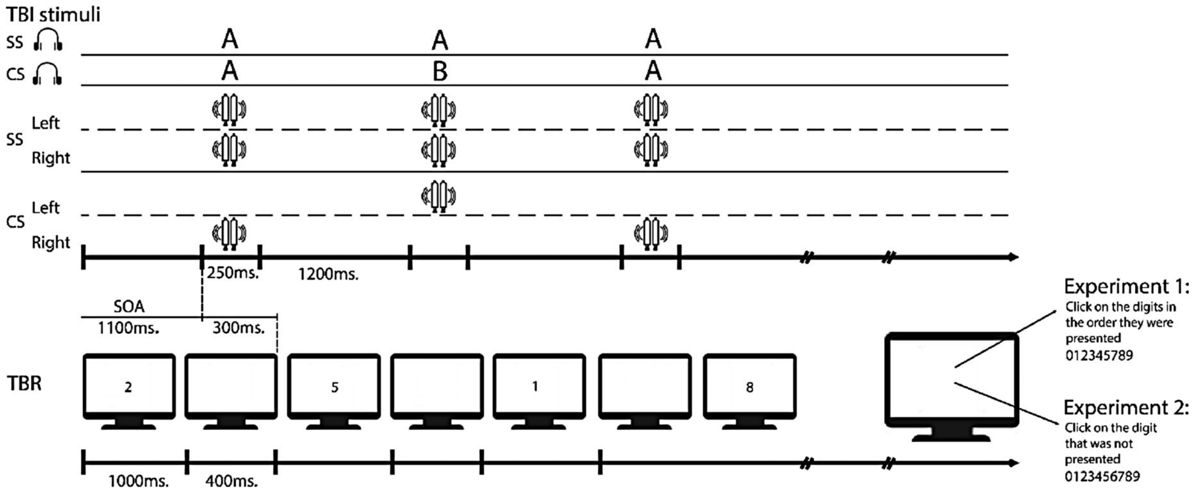

Figure 2. Schematic diagram of the stimulus presentation in Experiments 1 (serial recall) and 2 (missing item). The to-be-remembered (TBR) visual items were presented sequentially at the centre of the screen. To-be-ignored (TBI) stimuli could be either auditory (spoken letters) or tactile (vibrations). Auditory steady-state (SS) sequences consisted in the repetition of the letter 'A' whereas their vibrotactile counterpart consisted in the repeated presentation of the vibration simultaneously to both hands. Changing-state (CS) sequences consisted of the alternation of either the spoken letters 'A' and 'B' or vibrations between the two hands.

female voice at an approximately even pitch to 16-bit resolution at 22 kHz sampling rate and edited to a duration of 250 ms using SoundForge 10 software (Sony Creative Software).

Serial recall task

A traditional serial recall task was used whereby participants were required to recall nine visually-presented items in serial order. Each trial started with the presentation of a rectangle containing the text 'Warning' at the middle of the screen. Participants had to use the mouse to click in the rectangle to start. Following a mouse click the warning rectangle remained for 500 ms. In each trial, 9 out of 10 possible digits (0-9) were presented in random order. Each digit was presented for 1,000 ms, with an inter-stimulus interval of 400 ms. The vibrations/sounds were presented in the interval between digits with a stimulus onset asynchrony of 1,100 ms (see Figure 2), leading to a total of nine vibrations/sounds in each trial. Following a 100-ms gap from the offset of a vibration/sound, the next digit was presented. At the end of each visual sequence, participants were presented with the digits that had previously been presented in the list. All nine of the previously seen digits were presented and the participants' task was to click on the digits in the order that they were presented using a mouse pointer. When using the mouse to respond, participants were told to put down the handles on the table and then pick the handles up and hold them in the same manner as before. Once participants selected the ninth digit, the programme initiated the next trial.

Design and procedure

The experiment had five conditions: (i) A no-distractor condition, (ii) a steady-state vibrotactile sequence condition, (iii) a changing-state vibrotactile sequence condition, (iv) a steady-state auditory sequence condition, and (v) a changing-state auditory sequence condition. There were nine vibrations in total, leading to an uneven number of right- and left-hand vibrations, therefore the vibrations were counterbalanced across participants, such that half the participants had five vibrations delivered to the left hand and four vibrations to the right hand and vice versa for the other half. Whether the vibrations went from left-to-right or from right-to-left in the changing-state vibrotactile condition was counterbalanced across participants.

Also counterbalanced was whether the changing-state auditory sequence began with "a" (e.g. "a b a b a b a b a") or "b" ("b a b a b a b a b") and whether the participants heard a steady-state auditory sequence of "a" (e.g. "a a a a a a a a a"), or b (e.g. "b b b b b b b b b"). The modality of the steady-state and changing-state stimuli was blocked, such that half of the participants received two blocks of steady-state and changing-state vibrotactile sequences followed by two blocks of steady-state and changing-state auditory sequences, and the other half received the reverse order. Interposed between the two blocks of trials in either modality was a block of trials in which no vibrotactile or auditory stimuli were presented (no-distractor trials). There were 10 steady-state vibrotactile and 10 changing-state vibrotactile trials in each vibrotactile sequence block and 10 steady-state auditory and 10 changing-state auditory trials in each auditory sequence block. The order of the steady-state and changing-state trials was random within each block. There were 10 no-distractor trials.

Results

The raw data were scored according to the strict serial recall criterion: To be recorded as correct, an item had to be recalled in its original presentation position. The proportion of correct recall from the conditions in Experiment 1 are presented in Figure 3. Mean probability scores were lower in the changing-state vibrotactile condition (*M* = .64), than in the steady-state vibrotactile condition (*M* = .69). Moreover, mean scores in the changing-state auditory condition (*M* = .62) were lower than in the steady-state auditory condition (*M* = .66). Furthermore, performance in the changing-state vibrotactile and auditory conditions were lower than in the no-distractor condition (*M* = .67). However, scores in the steady-state vibrotactile and auditory conditions did not appear to differ from the no-distractor condition.

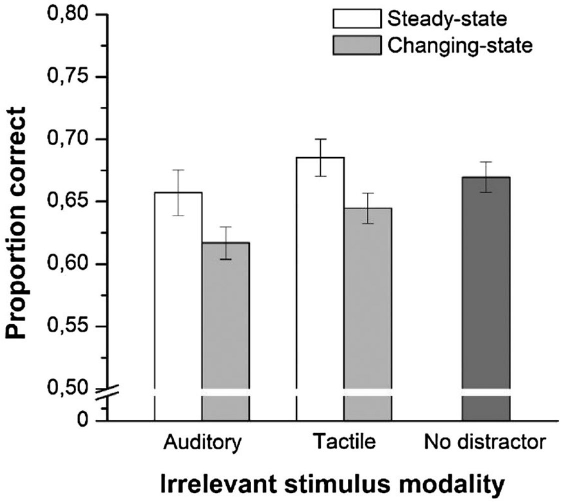

Figure 3. Proportion of correct recall in the five conditions of Experiment 1. The to-be-remembered visual sequence could be accompanied by (i) an irrelevant changing-state vibrotactile sequence, (ii) an irrelevant steady-state vibrotactile sequence, (iii) an irrelevant changing-state sound sequence, (iv) an irrelevant steady-state sound sequence, or (v) no distractors. The error bars represent 95% confidence intervals computed with the method of Cousineau (2005) and Morey (2008).

A preliminary one-way repeated-measures analysis of variance (ANOVA) revealed a main effect of condition, $F(4, 116) = 4.090$, $MSE = 0.005$, $p = .004$, $\eta_p^2 = .124$. Performance in the no-distractor condition differed significantly from performance in the changing-state vibrotactile condition ($p = .037$, 95% CI [-.002, .052], one-tailed), and the changing-state auditory condition ($p = .001$, 95% CI [.022, .083]). The no-distractor condition did not differ significantly from the steady-state vibrotactile condition ($p = .566$, 95% CI [-.055, .031]) or the steady-state auditory condition ($p = .381$, 95% CI [-.021, .052]).

A subsequent 2 (Modality: Vibration vs. Sound) × 2 (State: Steady vs. Changing) repeated-measures ANOVA revealed no main effect of Modality, $F(1, 29) = 2.56$, $MSE = 0.009$, $p = .120$, $\eta_p^2 = .081$. However, there was a main effect of State, $F(1, 29) = 11.38$, $MSE = 0.004$, $p = .002$, $\eta_p^2 = .282$, serial recall being poorer with changing-state than steady-state distractors. Crucially, there was no Modality × State interaction, $F(1, 29) < 0.01$, $MSE = 0.003$, $p = .990$, $\eta_p^2 < .001$, suggesting that the disruptive effect of changing-state distractors was of similar amplitude across modalities.

Pairwise comparisons were undertaken to investigate the magnitude of the changing-state effect size within each modality. Bayes factors were also computed for all pairwise comparisons to determine the relative level of support for the changing-state hypothesis. Bayes factor calculations were undertaken using software described in Dienes (2008). By default, this assumes a null hypothesis whereby the true population value is exactly zero. The Bayesian approach demands specificity about the hypothesis to be contrasted against the null. Although no prior research has investigated a changing-state effect in the context of vibro-tactile stimulation, we assumed that the effect would be similar in magnitude to the acoustical version of the effect. Therefore, we considered that the vibrotactile changing-state effect would vary in size between zero and the upper limit set by the acoustical changing-state effect. Our prediction was based on a half-normal distribution wherein predicting smaller effect sizes is more likely than larger effect sizes. Here, the estimate of the standard deviation of the p(population value|theory) was computed as a mean difference between the steady-state and changing-state conditions from the Bell et al. (2019; $M = .061$, $SE = .005$) and the mean of p(population value|theory) was set at 0. We chose that particular study because it was designed as a preregistered replication of the changing-state effect using a large sample ($n = 273$) and obtained a large changing-state effect ($f = 0.73$).

The changing-state effect was stronger in the vibrotactile condition, $t(29) = 3.22$, $p = .003$, Cohen's $dz = 0.588$, $BF_{10} = 29.18$, representing strong evidence for H_1, than it was the auditory condition, $t(29) = 2.33$, $p = .027$, Cohen's $dz = 0.436$, $BF_{10} = 3.39$, representing moderate evidence for H_1. Since the changing-state effect for auditory presentation is well-established any differences in Bayesian evidence between the vibrotactile and auditory condition must be treated cautiously.

Discussion

Experiment 1 showed that vibrotactile changing-state sequences disrupt serial short-term memory in comparison with steady-state sequences. The manifestation of this tactile changing-state effect was similar to the classical changing-state effect found in the auditory domain. This novel finding is consistent with the notion that interference arises through a conflict between the processing of inter-item relationships, not through a conflict between item-specific contents within short-term memory (cf. Jones & Tremblay, 2000). Within the auditory domain, the changing-state effect arises due to the presence of the pre-attentive, auditory-perceptual process of "object" or "stream" formation (see Bregman, 1990) and the deliberate, articulatory process of serially rehearsing the to-be-remembered material. The auditory-perceptual process involves unattended sound – such as sounds from the same location or of similar pitch – being organised into temporally extended streams. Thereafter acoustic changes between tokens within a single auditory stream yield cues as to their order within the stream, while a single repeated token conveys little information in relation to order within the sequence (Jones, 1999). A prerequisite for the manifestation of the auditory changing-state effect is the presence of a process responsible for maintaining the order of to-be-remembered information: serial rehearsal driven by covert articulation. These two similar order-based processes clash, resulting in impaired recall of item-order information of the to-be-recalled sequence (Jones & Tremblay, 1998). Bolstering this claim is the finding that only tasks that place heavy demands on a serial rehearsal strategy are vulnerable to the auditory changing-state effect (Beaman & Jones, 1997, 1998; Jones & Macken, 1993; see also Hughes & Marsh, 2020). The next step in the current series was therefore to explore the effects of changing-state vibrotactile distractors on a task that does not require memory for serial order.

Experiment 2

The primary goal of Experiment 2 was to further examine whether the pattern of disruption across the two different modalities of content (auditory and vibrotactile) is the same. To address the theoretical mechanism underpinning the cross-modal interference produced by a task-irrelevant distractor, one of two devices are typically deployed: Manipulating the nature of the focal task (Beaman & Jones, 1997; Jones & Macken, 1993; Jones et al., 1995) or manipulating the nature of the (potentially) interfering material (Jones et al., 1992). To gain some traction on the nature of disruption produced by vibrotactile sequences, both devices were employed across Experiments 1 and 2. Experiment 2 again involved varying the nature of the irrelevant material (to-be-ignored sound vs. to-be-ignored vibration), but also involved a change in the nature of the focal task. In Experiment 2, we adopted the missing item task[1] (Buschke, 1963). Like serial recall, this task involves the sequential presentation of a set of visual items in a random order. The particularity here is that all but one item from a closed set are presented (e.g. 9 of the 10 digits in the set 0–9) and the participant is asked to report the item missing from the list. Therefore, and contrary to serial recall, the missing item task does not necessitate the retention of serial order (Beaman & Jones, 1997; Buschke, 1963;

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[1] This task was originally called "the missing scan task" but has subsequently often been called "the missing item task" in the literature. As the task is about identifying an item that is missing from a closed set, the nature of the task arguably corresponds better with calling it "the missing item task", which is why we decided to remain consistent with this denomination.

Murdock, 1993), as suggested by its resilience to the impact of concurrent articulatory suppression (Klapp et al., 1983). This view that serial rehearsal is a rarely adopted strategy in the missing item task has also been corroborated by a study using self-report methodology (Morrison et al., 2016). Morrison et al. (2016) found that a minority of participants (28.6%) spontaneously use a serial rehearsal strategy when conducting the missing item task. Hughes and Marsh (2020) reported a slightly higher figure (40%) and found that those who reported a rehearsal strategy were also more susceptible to distraction by changing-state background sound. Nevertheless, the majority of participants self-report a non-rehearsal strategy when conducting the task, and are invulnerable to the changing-state effect. The missing item task arguably remains the most well-matched task to serial recall because it differs in only its retrieval conditions; its presentation conditions are identical (Beaman & Jones, 1997; Jones & Macken, 1993).

The main interest in exploiting the missing item task is that it provides a means to test the prediction of the interference-by-process account, whereby the disruptive power of changing-state distractors depends upon the focal task requirements for seriation. Consistent with this prediction is the finding that the report of the missing item in the context of the missing item task is immune to the presence of changing-state sound (Beaman & Jones, 1997; Hughes et al., 2007; Jones & Macken, 1993), including that conveyed via emotional prosody (Kattner & Ellermeier, 2018). This failure to obtain a changing-state effect cannot be accounted for by objecting that the missing item task is insensitive to distraction of any kind as its performance has been shown to be vulnerable to disruption via attentional capture (Hughes et al., 2007; Joseph et al., 2018; Vachon et al., 2017). Therefore, finding that changing-state vibrotactile stimuli fail to disrupt performance on the missing item task would add weight to the idea that the disruption produced by changing-state vibrotactile and auditory sequences are due to a common process.

Experiment 2 (as well as Experiment 3) also provides a test of a third account of the disruption changing-state vibrotactile stimuli produce to short-term memory – the attentional capture account (e.g. Bell et al., 2010; Bell et al., 2012; Chein & Fiez, 2010; Cowan, 1995; Elliott, 2002). On the attentional capture view, each token in a sequence that conveys token-to-token changes captures attention. This repeated capturing of attention from the task impairs performance, by dislocating attention from the to-be-recalled items (or drawing cognitive resources away from the memoranda; Bell et al., 2022). Since it is known that novel tactile input can capture attention (Ljungberg & Parmentier, 2012; Parmentier et al., 2011) similar to a sound that deviates abruptly from past sound exposure (see Hughes, 2014; Parmentier, 2014), one might consider the possibility that the changing-state vibrotactile effect is due to attentional capture. Given that deviant distractors can draw attention away from the prevailing activity regardless of the nature of this activity (Vachon et al., 2017), the attention-capture account of the changing-state effect predicts that changing-state vibrotactile distractors should disrupt performance on the missing item task (cf. Hughes et al., 2007), as they disrupted serial recall in Experiment 1. Therefore, a second goal of Experiment 2 was to test the hypothesis that the vibrotactile changing-state effect is due to a general attentional distraction because of the changing nature of the irrelevant input, by examining whether the phenomenon can generalise to a task that does not rely on or encourage serial rehearsal.

Method

The method was identical to that of Experiment 1, except as noted below.

Participants

Thirty students participated in the experiment in exchange for a small honorarium. None of them took part in Experiment 1. Three participants were removed for essentially performing at ceiling levels within the task. They were not replaced meaning that our sample allowed detection of a changing-state effect size of $f = 0.36$.

Materials and procedure

The serial recall task was replaced with a missing item task whereby participants were required to identify which number from the set 0–9 was not presented on a given trial. At the end of each visual sequence, participants had to click on which one of the 10 digits did not appear in the just-presented sequence, using a mouse pointer (see Figure 2). Participants had to click twice on the response-digit, a procedure chosen to minimise the possibility of erroneous mouse clicks.

Results

A visual inspection of Figure 4 reveals that the probability of correctly reporting the missing item was similar in the changing-state condition and the steady-state condition for both tactile and auditory modalities. Furthermore, this performance was similar in magnitude to the no-distractor condition. A preliminary one-way repeated-measures ANOVA revealed no main effect of condition, $F(4,\ 104) = 0.63$, $MSE = 0.013$, $p = .640$, $\eta_p^2 = .024$, thereby indicating no differences between any of the conditions. Without surprise, the follow-up 2 (Modality: Vibration vs. Sound) × 2 (State: Steady vs. Changing) repeated-measures ANOVA revealed no main effect of Modality, $F(1,\ 26) = 1.60$, $MSE = 0.003$, $p = .218$, $\eta_p^2 = .058$, no main effect of State, $F(1,\ 26) = 0.003$, $MSE = 0.008$, $p = .959$, $\eta_p^2 < .001$, and no interaction, $F(1,\ 26) = 0.115$, $MSE = 0.010$, $p = .738$, $\eta_p^2 = .004$.

Pairwise comparisons were undertaken to investigate the Bayesian support for the null over the alternative hypothesis in relation to the changing state effect as a function of modality. The changing-state effect was absent in the vibrotactile condition, $t(26) = -0.394$, $p = .697$, Cohen's $dz = -0.076$, $BF_{10} = 0.32$, indicating moderate evidence for H_0, and in the auditory condition, $t(26) = 0.176$, $p = .862$, Cohen's $dz = 0.034$, $BF_{10} = 0.47$, reflecting anecdotal evidence for H_0.

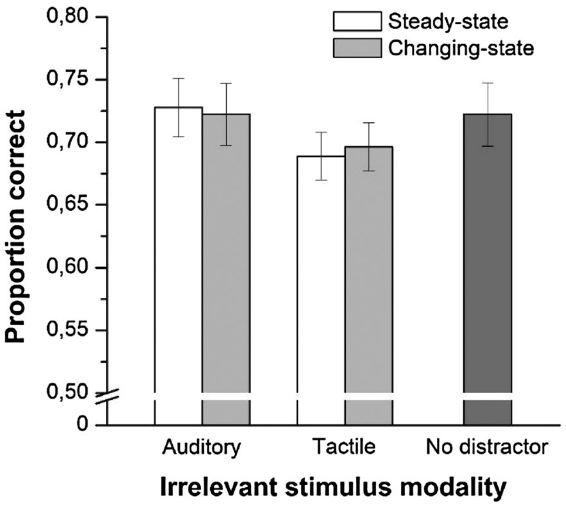

Figure 4. Proportion of correct recall of the missing item in the five conditions of Experiment 2. The to-be-remembered visual sequence could be accompanied by (i) an irrelevant changing-state vibrotactile sequence, (ii) an irrelevant steady-state vibrotactile sequence, (iii) an irrelevant changing-state sound sequence, (iv) an irrelevant steady-state sound sequence, or (v) no distractors. The error bars represent 95% confidence intervals computed with the method of Cousineau (2005) and Morey (2008).

Discussion

Experiment 2 demonstrated the immunity of the missing item task to disruption via the presence of changing-state vibrotactile and auditory stimuli. This gels with previous research (Hughes & Marsh, 2020; Morrison et al., 2016) and is consistent with the assumption that participants typically do not use a serial rehearsal strategy when conducting the task (Morrison et al., 2016). That changing-state vibrotactile stimuli, like changing-state auditory stimuli, have no discernible impact on a task that does not involve the retention of serial order supports the view that the common process of serial order subsumes the pattern of disruption across the two modalities of content (auditory and tactile). At the same time, the sensitivity to disruption of tasks that require serial order processing is inconsistent with the notion that the changing-state vibrotactile effect is one that could be attributable to a generic form of attentional capture ensuing from the changing nature of the vibrotactile input (cf. Bell et al., 2010, 2012; Chein & Fiez, 2010).

Experiment 3

The goal of Experiment 3 was twofold. First, the vibrotactile changing-state effect is a novel form of distraction that was observed in Experiment 1 but not in Experiment 2. It therefore needs to be replicated. To do so, we chose the probed order task (e.g. Jones & Macken, 1993) as a measure of short-term memory. This task is similar to serial recall as it involves presenting a list of familiar verbal items in an unfamiliar order. Following the last item, one item from the presented list is re-presented and the requirement is to report the item that followed it in the list (e.g. Murdock, 1968). As for serial recall, the probed order task is characterised by serial rehearsal being the dominant strategy for efficient performance of the task (e.g. Beaman & Jones, 1997). This view is supported by the fact that variables thought to impair serial order processing such as articulatory suppression and talker variability disrupt performance on the task (Hughes et al., 2011; Macken & Jones, 1995). Although it requires the report of a single item as does the missing item task, the probed order task, unlike the missing item task, is sensitive to disruption from the changing-state properties of irrelevant sound (e.g. Beaman & Jones, 1997; Elliott et al., 2016; Jones & Macken, 1993). Therefore, from an interference-by-process standpoint, the presentation of changing-state vibrotactile distractors should also produce disruption in the context of the probed order task.

Experiment 3 was also designed to further test the attention-capture account of the vibrotactile changing-state effect. In the previous experiments, changing-state vibrotactile stimuli were always presented in a predictable fashion (e.g. left-right-left-right-left-right). Yet predictability is a key determinant of attentional capture. In the auditory domain, the attentional response to a deviant stimulus diminishes with increasing the predictability of – and hence expectancy for – that deviant sound (Vachon et al., 2012). Furthermore, there is evidence that attentional capture by sounds is modulated by participants' expectations (Hughes et al., 2013; Nöstl et al., 2012). One could therefore argue that the absence of a vibrotactile changing-state effect in Experiment 2 was attributable to the high predictability of the vibrotactile stimuli (albeit the same type of vibrotactile changing-state sequences did produce disruption in Experiment 1).

According to the interference-by-process view, however, the predictability of the vibrotactile stimulus sequence should not matter; at least it does not for the changing-state effect as produced by an auditory sequence (Jones et al., 1992; Marsh et al., 2014; Hughes & Marsh, 2020). Even predictable sequences with a very limited degree of change are powerful enough to produce a changing-state effect (Tremblay & Jones, 1998). To control for the possibility that predictability also contributes to the disruption of short-term memory by vibrotactile stimuli, the present experiment contrasted the disruptive impact of two types of changing-state sequence. The changing-state sequence could either be 'predictable', when the presentation of the vibrations alternated between the two hands (left-right-left-right etc.), or 'unpredictable', when the vibrations were presented randomly across the two hands. On the view that changing-state effects produced from auditory stimulation arise with alternating sound sequences (e.g. "a b a b a b a b a") involving only minimal change (Tremblay & Jones, 1998), we hypothesised that the magnitude of the changing-state effect should be independent of the predictability of the vibrotactile sequence. Contrary to Experiments 1 and 2, distractors were exclusively presented in the tactile domain in the present experiment.

Method

The method was identical to that of Experiment 1, except as noted below.

Participants

Eighty-four students participated in the experiment in exchange for a small honorarium. None of them took part in the previous experiments. The participants were divided into two groups: one received a predictable changing-state sequence of vibrotactile stimuli whereas the other received an unpredictable changing-state sequence of vibrotactile stimuli. This time, the sample size was determined based on the sensitivity to detect a two-way interaction between vibrotactile condition and changing-state predictability. With 42 participants in the predictable group, 42 participants in the unpredictable group, and given $\alpha = .05$ and a power level of .95, it was possible to detect an interaction of size $f = 0.20$. Unfortunately, six participants from each group were lost because either they evidently misunderstood the task instructions or their data were highly unrepresentative (they performed at floor in all experimental conditions). With now 36 participants in each group, it was then possible to detect an interaction of size $f = 0.22$.

Materials, design and procedure

At the end of each visual to-be-remembered 9-item sequence, participants were presented with one of the digits (the probe) that had previously been presented in the list. All digits, 0-9, were also presented, next to the probe, and the participants' task was to identify the digit that had followed the probe at presentation, by using the mouse and clicking on the appropriate digit. As in Experiment 2, participants had to click twice on the response-digit. Each serial position was probed equiprobably.

The experiment had three conditions (see Figure 5): A no-distractor control condition, a

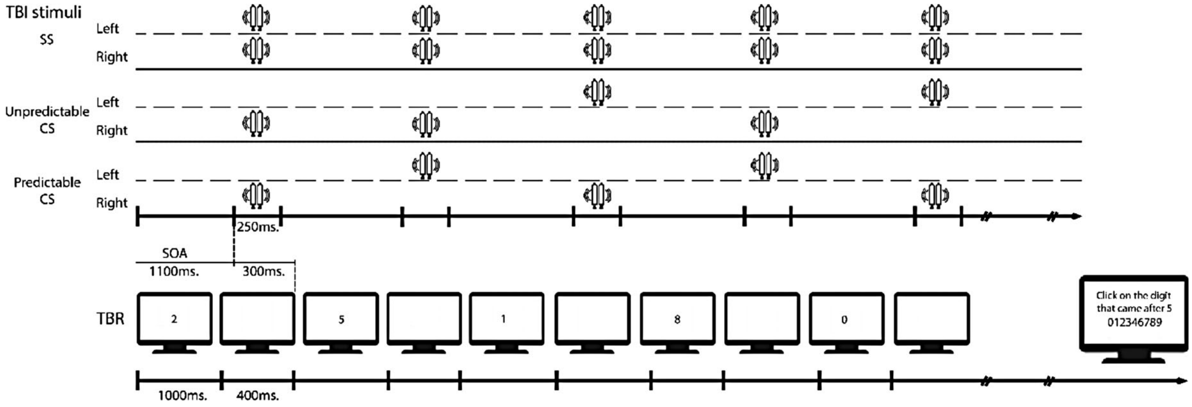

Figure 5. Schematic diagram of the stimulus presentation in Experiment 3 (probed order recall). The to-be-remembered (TBR) visual items were presented sequentially at the centre of the screen. To-be-ignored (TBI) stimuli consisted of a sequence of vibrations presented to both hands. In steady-state (SS) sequences, vibrations were repeatedly presented to both hands simultaneously. In changing-state (CS) sequences, vibrations alternated between the two hands in either a regular (predictable) or random (unpredictable) fashion.

steady-state vibrotactile sequence condition, and a changing-state vibrotactile sequence condition. There were two types of changing-state vibrotactile sequences: a predictable (i.e. non-random) sequence and an unpredictable (i.e. random) sequence. In the predictable sequence, the vibrations alternated between the two hands (e.g. left-right-left-right-left-right-left-right-left), as in the previous experiments. In the unpredictable sequence, each vibration had an equal probability of being presented to the left as to the right hand (e.g. left-left-right-right-left-right-right-left-left). Half of the participants received the predictable changing-state vibrotactile sequences while the other half were presented with the unpredictable sequences. The three experimental conditions were presented in blocks (i.e. the trials did not alternate between conditions; all 24 trials for one condition were presented before changing to the next condition). The order of the three conditions was counterbalanced between participants with a Latin square design.

Results

For participants who were presented with a predictable changing-state vibrotactile stimulus, mean probability scores were lower in the changing-state condition ($M = .57$), than in the steady-state condition ($M = .59$) which in turn were lower than in the no-distractor condition ($M = .61$). The tendency was similar for participants who were presented with the unpredictable changing-state sequence, but while the mean probability scores for them were lowest in the changing-state condition ($M = .57$), the scores in the steady-state condition ($M = .63$) were similar to the scores in the no-distractor condition ($M = .63$). The two groups had almost identical scores in the changing-state condition, $t(70) = 0.03$, $p = .975$, and the difference between the changing-state condition and the no-distractor condition was similar in magnitude for the two groups ($M = .04$ versus $M = .05$), $t(70) = 0.58$. $p = .565$.

A preliminary 3 (Vibrotactile condition) × 2 (Group: predictable vs. nonpredictable) mixed ANOVA did not reveal a significant interaction between Vibrotactile condition and Group, $F(2, 140) = 0.66$, $MSE = 0.011$, $p = .520$, $\eta_p^2 = .009$. Therefore, data from the two groups were collapsed. As can be seen in Figure 6, probe recall was impaired by the changing-state vibrotactile sequences in comparison with the steady-state condition and the no-vibration control condition. The steady-state vibrotactile sequence did not produce disruption. These results were confirmed by a repeated-measures ANOVA across the three vibrotactile conditions, $F(2, 142) = 3.87$, $MSE = 0.01$, $p = .023$, $\eta_p^2 = .052$. The changing-state condition was significantly different from the steady-state condition ($p = .043$, 95% CI [.07, .001], $dz = 0.242$, $BF_{10} = 1.94$, representing anecdotal evidence for the changing-state hypothesis), and from the no-vibration control condition ($p = .006$, 95% CI [.08, .01], $dz = 0.333$) while there was no evidence for a difference between the steady-state condition and

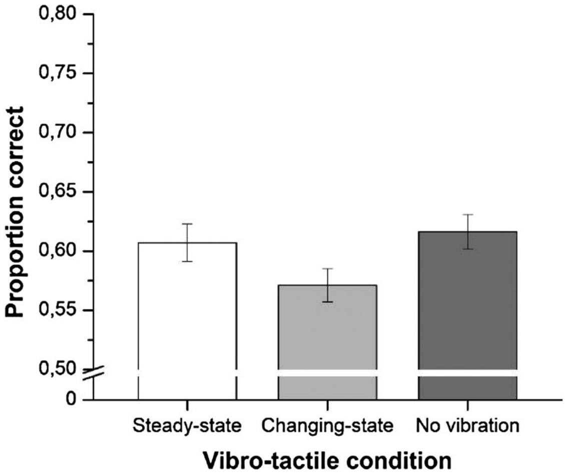

Figure 6. Proportion of correct recall on the probe task in the three conditions of Experiment 3. The to-be-remembered visual sequence could be accompanied by (i) an irrelevant changing-state vibrotactile sequence, (ii) an irrelevant steady-state vibrotactile sequence, or (iii) no vibration. The error bars represent 95% confidence intervals computed with the method of Cousineau (2005) and Morey (2008).

the no-vibration control condition ($p = .608$, 95% CI [.03, .05], $dz = 0.061$).

Discussion

By revealing the disruptive power of vibrotactile changing-state distractors on probed order recall, the results of Experiment 3 not only replicated the novel finding of Experiment 1, that vibrotactile sequences can produce changing-state effects, but also extended the effect to another short-term memory task that requires serial rehearsal. The evidence for the effect was weaker in comparison with the effect found in the context of the serial recall task in Experiment 1, as indicated in particular by the Bayesian statistics, suggesting that the probe task might be less sensitive to disruption. Still the conceptual replication of the vibrotactile changing-state effect is theoretically important as it suggests that this novel effect is robust and replicable. The fact that the vibrotactile changing-state effect was reinstated in a task promoting the use of a serial rehearsal strategy is consistent with the interference-by-process view of short-term memory (e.g. Jones & Tremblay, 2000).

A key finding of the present experiment was that the predictability of the vibrotactile changing-state sequence appeared to have little if any effect. Making the vibrotactile stimuli less predictable within changing-state sequences should have boosted their attention-grabbing power (cf. Nöstl et al., 2012; Vachon et al., 2012), yet such a manipulation failed to modulate the magnitude of the changing-state effect. This result provides further evidence against an attention-capture account of the changing-state effect (cf. Bell et al., 2010, 2012, p. 2022; Chein & Fiez, 2010).

General discussion

The series of experiments presented here are the first to explore in depth the effects of task-irrelevant vibrotactile stimuli on visual-verbal short-term memory and the functional similarity between vibrotactile and auditory distraction in this context. The results from three experiments revealed that short-term memory for a visual sequence is more disrupted by a changing-state vibrotactile sequence compared to a steady-state tactile sequence. The impact of changing-state vibrotactile distraction is similar in magnitude to that of auditory distraction (Experiment 1); the interference between vibrotactile stimuli and short-term memory appears to concern recall of item-order rather than item-identity (Experiment 2); and the predictability of the vibrotactile stimuli does not appear to modulate the magnitude of the effect (Experiment 3). This vibrotactile changing-state effect appears to be genuine as the Bayes Factor analysis performed on the combination of the samples from Experiments 1 and 3 ($M = .0373$, $SE = .0128$,) indicated strong support for the changing-state hypothesis ($BF_{10} = 11.65$).

Implications for theories of interference in short-term memory

The evidence of disruption to verbal memory produced by vibrotactile stimulation – whether steady- or changing-state – undermines the interference-by-content model. This is because any such effect would violate the notion that the two sets of material must be sufficiently similar in order to interfere with each other (e.g. Baddeley, 1986; Page & Norris, 2003). The finding that changing- but not steady-state vibrotactile stimuli disrupts verbal serial short-term memory offers further evidence for the interference-by-process view over the interference-by-content view. The interference-by-content models have attempted to accommodate or explain the effect of changing-state irrelevant non-speech sound such as tones on verbal serial recall as being due to the fact that such sound is similar enough to speech to enter the same phonological store as the verbal to-be-remembered items (e.g. Page & Norris, 2003). It is clearly a stretch too far to suppose that changing-state vibrotactile stimuli are similar enough to speech to gain access to a phonological store.

Similarly, according to the feature model (Neath, 2000), only speech produces interference-by-content: The disruption of serial short-term memory by sequences of tones is attributed to attentional capture. Therefore, the interference-by-content part of the model cannot be applied to changing, non-speech, vibrotactile stimuli (the model also has difficulties explaining findings from studies demonstrating that the changing-state effect in the context of auditory distraction is not due to attentional capture; Hughes et al., 2005, 2007, p. 2013; Marois et al., 2019, 2020). It should be mentioned though, the Feature model can be extended to account for non-speech irrelevant stimuli as well through recourse to an 'attention' construct that represents the net available resources for attention (*a*; Neath, 2000). To model the impairment produced by non-speech distracters, adjustment is made only to the *a* parameter. Similarly, the impairment produced by changing-, over steady-, state distracters is also modelled by adjustments to the *a* parameter with the assumption that single repeated items (e.g. steady-state stimuli) are easier to ignore – and thus will divert attention less – than a stream of items that changes from one token to the next (e.g. changing-state stimuli; Neath, 2000).

On the modular approach of Bancroft and Servos (2011), feature overwriting should not occur between visual and vibrotactile stimuli for two reasons. First, visual-verbal items should not gain access to a purported vibrotactile short-term memory and vibrotactile stimuli should not access the storage space for visual-verbal information wherein feature overwriting takes place. Second, if vibrotactile stimuli are only represented by frequency feature units (Bancroft & Servos, 2011), there should be no overwriting of representations coding visual-verbal items regardless of whether the stimuli access the same working memory space as visual-verbal items. That changing vibrotactile stimuli have the same effect as changing auditory stimuli is therefore highly problematic for the interference-by-content class of model. The changing-state vibrotactile effect instead supports an alternative, interference-by-process, account that does not appeal to interference-by-content within (or outside of) content-defined stores.

Another precept of the interference-by-content view is that the degree of feature similarity between the memoranda and the task-irrelevant information underpins disruption of recall (Baddeley, 2012; Neath, 2000; Oberauer, 2009). The results reported here are difficult to accommodate within this variety of interference-by-content view. Short-term memory is disrupted by task-irrelevant information even when the to-be-recalled and the distracting information are encoded into drastically different forms and the representational codes of vibrotactile and visual-verbal stimuli are unlikely to overlap. Thus, we reach the same general conclusion as Jones et al. (1995), who demonstrated that changing-state irrelevant sound disrupted the recall of sequentially presented locations of dots whose representations (in the absence of the possibility of verbal recoding) were unlikely to overlap with that of the auditorily-presented material. While some of the results reported by Jones et al. have proven difficult to replicate (Guitard & Saint-Aubin, 2015; Marsh et al., in revision; Meiser & Klauer, 1999), our results support the notion that short-term memory processing is unitary (Vergauwe et al., 2010), rather than divided into functionally distinct and specialised subsystems (Baddeley, 2012; Baddeley & Hitch, 2019; Tulving, 2002). The unitary views hold that short-term memory for verbal and spatial information is functionally equivalent, with changing-state information being similarly represented in an amodal workspace wherein interference occurs when functionally similar processes come into conflict (Hughes, 2014; Jones & Macken, 1993; Marsh et al., 2008; Marsh et al., 2008).

Moreover, of importance for particular instantiations of the interference-by-content account (e.g. Baddeley, 1986; Page & Norris, 2003), the task-irrelevant material does not have to contain phonological, or even phonological-like, information to produce a changing-state effect: Interference depends on the inter-item relationships and not on the item-specific contents. The changing-state vibrotactile effect can only be accommodated by an interference-by-content model under the assumption that order information within the task-irrelevant sequence is retained in a short-term memory store and comes into conflict with order information embedded in the task-relevant sequence, even though the item-specific features are clearly distinguished. Under this assumption, it would be difficult to remain faithful to the idea of separate (modality-specific) storage spaces within a cognitive system.

Therefore, the current findings appear to cohere better with the interference-by-process view in which stimuli in various forms (auditory-verbal, auditory-nonverbal, visuospatial, subvocal, and tactile) nonetheless share a common level of representation within a cognitive system (Jones, 1994; Jones et al., 1996). According to this approach, interference is assumed to take place within an amodal workspace, not within modality-specific subcomponents within a hypothetical architecture of short-term memory. Here, the importance is placed on the organisation of the to-be-recalled material, rather than the modality within which it was presented. Retaining information over the short term requires the co-opting or exploitation of processes designed for non-memory functions. For verbal material, gesture planning systems (particularly that of speech planning) are used to graft constraints onto – that is, increase the transitional probabilities between the elements of – the to-be-remembered material to facilitate its recall as a sequence (Hughes et al., 2009). For visuospatial recall, the operation of an ocular, sequential motor plan is provided by eye movements (Morey et al., 2018; Tremblay et al., 2006).

Regardless of the modality of the to-be-recalled items, in each case the obligatory perceptual organisation of irrelevant sound yields order cues that come into conflict with those generated by various motor systems (subvocal for verbal material, ocular for visuospatial material) that are co-opted to facilitate short-term retention (cf. Hughes & Marsh, 2017). Accordingly, the extension here of the changing-state effect to the tactile domain may be taken as evidence, albeit indirect, that the automatic perceptual organisation of vibrotactile sequences can also yield order information that interferes with the use of general-purpose motor systems involved in short-term ordered retention of visual-verbal material. That the cognitive representation of the to-be-ignored vibrotactile modality is arguably not verbal, phonological or speech/sound-like, yet still disrupts serial recall, supports the notion that the representation of the irrelevant sequential information that gives rise to disruption is amodal and code-independent. Sequence information from the tactile modality is also extracted and comes into conflict with verbal short-term memory.

While there are several commonalities between the auditory and somatosensory system – for example, both have good temporal resolution – the evidence for whether the same grouping rules that apply in auditory perception apply to tactile perception is incomplete and inconsistent (Lin & Kashino, 2012). While Lin and Kashino (2012) found that tactile stimuli applied to different locations on the body appear to become segregated into two streams, the results of our study suggest that they form a single stream, grouped over time, within which the temporal order of information is encoded. One explanation as to why our conclusion is different from that of Lin and Kashino may lie in presentation rate. Lin and Kashino used a much faster presentation rate (75-ms long [with 10-ms ramps] vibrations with 75-ms silent gaps) than that adopted in the current experimental series. Fast presentation rates are known to promote stream segregation (e.g. Bregman, 1990; Moore & Gockel, 2012), while the slower presentation rates used in the current study appears to have led to a single stream thereby preserving the encoding of the temporal order of information and endowing it with the capacity to produce an interference-by-(serial-order)-process.

Attention capture or interference between processes?

An attentional capture mechanism has been proposed as an explanation of the changing-state effect as it arises in the context of auditory distraction (e.g. Bell et al., 2010, 2012, 2022; Chein & Fiez, 2010; Cowan, 1995; Elliott, 2002). While there is indeed evidence in the form of effects of habituation (Röer et al., 2014a; Sörqvist et al., 2012) and of foreknowledge (Röer et al., 2015) that attentional capture is involved in the disruption of short-term memory by complex auditory distractors (e.g. natural speech), the classic changing-state-effect that is investigated here cannot be explained by such a mechanism (Hughes, 2014; Hughes & Marsh, 2020).

Sound that deviates abruptly from an otherwise constant sound stream (such as the sound “m” in a sound stream comprising the spoken letters “k k k m k k k”) can disrupt short-term memory, but this deviation effect appears to be functionally distinct from the changing-state effect (Hughes et al., 2007; Marois et al., 2019, 2020). According to the duplex-mechanism account of auditory distraction, the deviation effect is caused by attention capture while the changing-state effect is caused by interference between two clashing processes: the processing of change between successive segments of the auditory-perceptual input (Bregman, 1990) and the deliberate serial rehearsal of the to-be-recalled items (Hughes, 2014; Macken, 2014). Consequently, changing-state sound causes interference even though it does not draw attention (Macken et al., 2003), because the interference is a product of a conflict between these two sets of sequence processes. It is also useful to point out here the distinction between stimulus-aspecific attentional capture and stimulus-specific attentional capture (Hughes, 2014). In the former, violations of expectations capture attention (e.g. Nöstl et al., 2012; Vachon et al., 2012) whereas for the latter, the nature of the material per se bestows it with attentional capturing power. Auditory deviants and natural speech disrupt performance on short-term memory tasks regardless of serial memory requirements (Vachon et al., 2017), whereas simple changing-state sound sequences (e.g. letters) only produce more disruption than steady-state sound sequences to the extent that the task requires serial rehearsal or other means of serial reproduction of the memoranda (Hughes et al., 2007; Hughes & Marsh, 2020). Unlike stimulus-aspecific attentional capture where violation of expectation causes attentional capture (Nöstl et al., 2012; Parmentier et al., 2022; Röer et al., 2014b; Vachon et al., 2012), even highly predictable changing-state sound sequences (such as an alternation between two items; a, b, a, b, a, b, a, b) produce more disruption of serial short-term memory than steady-state sound sequences (Tremblay & Jones, 1998; see also Experiment 1).

Perhaps the major challenge to any account assuming that the vibrotactile changing-state effect is one of attentional capture is that the effect was not observed in a task that does not require a sequencing process – the missing item task (Experiment 2). If the changing-state vibrotactile effect was due to attentional capture, then it would be expected to manifest on a whole range of focal tasks that do not call upon any obvious sequencing component, and thus behave as the auditory deviant effect (see Vachon et al., 2017, for a discussion). However, the vibrations in the changing-state sequences in the current series of experiments were presented in a temporally predictable fashion (as the auditory items in Vachon et al., 2017). While participants could not predict which hand the vibrations would be presented to, and were hence unpredictable in this sense, the vibrations were still temporally predictable (all vibrations were presented with the same rhythmic timing). This temporal predictability yet spatial unpredictability should attenuate any role of attention capture. Future research should explore the effects of irrelevant vibro-tactile sequences on short-term memory incorporating changing-state vibrations that are neither spatially nor temporally predictable. Manipulating the temporal features of the vibro-tactile distracter could also reveal how rhythm may contribute to and underpin the effect. Moreover, the synchronisation between the onset of to-be-recalled items and to-be-ignored auditory distracters modulates auditory distraction (Marsh et al., 2015). Hence, one possibility is that synchronised onset of to-be-recalled items and task-irrelevant vibrations contributes to a conflict between the two streaming processes underpinning retention and distractor processing. To further explore the possible role of attention capture in the effects of vibrotactile stimuli on short-term memory, future research could explore the role of habituation. The role of habituation in auditory distraction has been extensively debated, with evidence suggesting that habituation may (Bell et al., 2012) or may not (Tremblay & Jones, 1998) play a role for the changing-state effect. Future research could address the extent to which habituation plays a role to the vibrotactile changing-state effect and while so doing, for example, test whether there is a difference between having the participants respond vocally or manually to the short-term memory task. Furthermore keeping the hands on the handles across the experiments could perhaps influence the effects of habituation to the vibrotactile stimuli.

Implications for unitary versus multi-component views of short-term memory

The primary focus of the work of Jones et al. (1995) was to critically reappraise the multi-agency view held by the Working Memory model (Baddeley, 1992; Baddeley & Hitch, 2019). This view proposes a fractionation of working memory whereby different stores are dedicated to classes of events usually specified by their modality of origin. On this view – that certain classes of events are stored independently of others – greater interference should arise from secondary tasks that draw upon the same storage space. For example, a visuospatial secondary task should interfere more with a visuospatial focal task, than should an auditory-verbal secondary task. However, at odds with this view, Jones et al. found that changing-state spatial tapping produced greater disruption of both visual-verbal serial recall and visuospatial serial recall than steady-state spatial tapping (Experiment 2). In the latter case, participants were required to recall the correct sequence of a series of dots presented in different spatial locations. Furthermore, changing-state mouthed articulatory suppression produced greater disruption than steady-state mouthed suppression of both visual-verbal and visuospatial serial recall (Experiment 3). Finally, and most relevant for our current investigation, was that considering this, Jones et al. argued for a unitary model wherein short-term memory for verbal and spatial information is functionally equivalent. Despite the substantial impact of this paper, several studies have failed to replicate Jones et al.'s findings (Guitard & Saint-Aubin, 2015; Kvetnaya, 2018; Marsh et al., in revision; Meiser & Klauer, 1999; see also Georgi et al., 2022).

Manual tapping can have functionally similar effects on short-term memory as irrelevant speech (Surprenant et al., 2008). Moreover, similar to a changing-state effect in the context of auditory distraction, complex (e.g. syncopated) tapping can have larger disruptive effects on short-term memory than simple tapping (Alloway et al., 2010; Saito, 1994; Surprenant et al., 2008). The vibrotactile changing-state effect reported here in combination with the functional similarities between concurrent manual tapping and concurrent to-be-ignored background stimuli provides further evidence for a unitary view of short-term memory, wherein interference between information from clearly distinct modality sources arises within an amodal, unitary workspace. If it can be assumed that syncopated tapping gives rise to a perceptual stream within which order cues are particularly strongly represented, then the greater interference that arises from such tapping (Alloway et al., 2010; Surprenant et al., 2008) may also align with the interference-by-process approach while being difficult to reconcile within an interference-by-content view of short-term memory disruption. For example, on the Working Memory model (Baddeley, 1986, 1992, 2012) there is no reason why syncopated tapping should affect the phonological loop (Surprenant et al., 2008).

Conclusion

The results presented here have implications for two central debates in contemporary psychology: One of the central debates concerns whether the cognitive system is unitary (Jones et al., 1995; Vergauwe et al., 2010) or whether it is fractionated into functionally distinct and specialised subsystems (or multiple components; Baddeley, 2012; Baddeley & Hitch, 2019; Tulving, 2002); the other concerns whether interference and other cognitive phenomena are best explained the function of cognitive systems (Baddeley, 2012; Tulving, 2002) or by attribution to cognitive processes (Craik & Lockhart, 1972; Jones & Macken, 1993). Two sources of evidence that have been used to adjudicate between these perspectives come from studies on similarities and differences between stimulus-source modalities and studies of interference between representations. Unitary views of cognition hold that short-term memory for verbal and spatial information is functionally equivalent (Jones et al., 1995) while multi-component views of cognition assume that resources from different modalities are functionally distinct (Baddeley & Logie, 1999; Guérard & Tremblay, 2008; Meiser & Klauer, 1999). The results from the current series of studies undermine the multiple-component views which suggest that interference occurs when memory representations overlap and share similarity of content (Baddeley, 2012; Neath, 2000; Oberauer, 2009; Oberauer & Kliegl, 2006). Vibrotactile sequences whose representations are unlikely to share any similarity in content with that of visual-verbal items, produce disruption of serial recall, providing they change-in-state. Instead, the results reported here support a unitary view according to which interference occurs within an amodal workspace within which functionally similar processes come into conflict (Hughes, 2014; Jones & Macken, 1993; Marsh et al., 2008, 2009). The results suggest that a common serial process subsumes the pattern of disruption across the two modalities of content (auditory and vibrotactile), a result that also undermines an attentional capture account. The experiments support the idea that perceptual organisation principles (streaming/grouping of individual stimuli into objects) – that appear to underpin the changing-state effect as it manifests in distraction from sound – are also present for tactile perception (Gallace & Spence, 2011).

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Data availability statement

The data that support the findings of this study are available from https://uclandata.uclan.ac.uk/id/eprint/363.

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