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No evidence for a vibrotactile changing-state effect in serial recall: a multi-experimental replication attempt

Emil Skog[a], John E. Marsh[a,b,c], Jessica K. Ljungberg[a] and Patrik Sörqvist[a,d]

[a]Department of Health, Learning and Technology, Luleå University of Technology, Luleå, Sweden; [b]Human Factors Laboratory, School of Psychology and Humanities, University of Lancashire, Preston, UK; [c]Faculty of Society and Design, Bond University, Gold Coast, Australia; [d]Department of Building Engineering, Energy Systems and Sustainability Science, University of Gävle, Gävle, Sweden

ABSTRACT
One way to develop theories of forgetting in short-term memory is to introduce novel sources of distraction. A recent study reported a *vibrotactile changing-state effect*, suggesting that a sequence of irrelevant vibrations can disrupt visual-verbal serial recall if it contains variation. The present study aimed to replicate and extend this finding. But Experiment 1 found no evidence of a vibrotactile changing-state effect in visual-verbal serial recall. The effect was also absent in a direct replication of the original report (Experiment 4) and with a visual-spatial serial recall task (Experiment 2). Experiment 3 implemented further variation in vibrotactile properties, varying the timing, strength and spatial location of vibrations, yet produced no disruption. A Bayesian random-effects meta-analysis across all available experiments further supported the null hypothesis. These results suggest that the previously reported effect may reflect a false positive, and contribute to theory refinement by identifying potential boundary conditions for vibrotactile distraction.

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Short-term memory; vibrations; distraction; tactile perception; interference-by-process

Introduction

Short-term memory is a fundamental psychological function that allows us to maintain a limited amount of information in an active and available state. This memory process can be disrupted by new incoming perceptual information. A central debate in modern cognitive psychology concerns what kinds of new information come into conflict with information held in short-term memory (Oberauer et al., 2018). According to one set of views, interference in short-term memory occurs on the basis of similarity of content. That is, new information can interfere with stored information if both streams share overlapping memory representations, leading to potential overwriting (Anderson, 1983; Baddeley, 2012; Cowan, 1999; Hanley & Bakopoulou, 2003; Henson et al., 2003; McGeoch, 1942; Mensink & Raaijmakers, 1988; Neath, 2000; Oberauer, 2009; Oberauer et al., 2004; Oberauer & Kliegl, 2006; Oberauer & Lange, 2008; Page & Norris, 2003; Salamé & Baddeley, 1982; Vergauwe et al., 2010).

Another view proposes that interference in short-term memory arises from similarity of processes, that is, from competing cognitive activities or actions that come into conflict. According to this account, a serial memory process depends on maintaining the order of information, and this can be disrupted by a distractor sequence that carries irrelevant serial order information (Hughes et al., 2005, 2007; Jones & Macken, 1993; Jones & Tremblay, 2000; Marsh et al., 2009; Marsh, Vachon, et al., 2024; Sörqvist, 2010). An example of this is the changing-state effect (Jones et al., 1992; Tremblay & Jones, 1998), whereby a sequence of steady, unchanging, irrelevant auditory tokens (e.g. “a a a a a a a a”) cause minimal, if any distraction, but a sequence of alternating tokens (e.g. “a b a b a b a b”) markedly disrupts serial recall. This illustrates that it is not necessarily the content of the irrelevant distractor (e.g. the identity of the tokens) that produces interference, but rather the presence of irrelevant serial information within the distractor stream. A requirement for the changing-state effect is that the tokens (a’s and b’s) within the distractor sequence are perceptually grouped as a single varying stream rather than perceptually segregated into multiple steady streams (one stream of a’s and a separate stream of b’s).

Although the changing-state effect is often taken as strong evidence for interference-by-process accounts,

CONTACT John E. Marsh JEMarsh@uclan.ac.uk Human Factors Laboratory, School of Psychology and Humanities, University of Lancashire, Room 108, Darwin Building, Marsh Lane, Preston, Lancashire PR3-5FF, UK

it is also compatible with attentional capture views (Cowan, 1995). In this view, task performance is disrupted not through mnemonic interference, but because salient or unexpected events involuntarily draw attention away from the focal task. Such distraction can occur even when the distractor shares neither content nor structural similarity with the memoranda (e.g. Hughes, 2014; Parmentier, 2008). While conceptually distinct from interference-by-process, attentional capture is often examined within the same paradigms and has been used to explain effects of deviant sounds or large token sets, where perceptual variability heightens salience (e.g. Bell et al., 2019a; Hughes et al., 2005, 2007). In these frameworks, each item-to-item change in a distractor stream constitutes a "mini-deviant" that elicits repeated orienting responses (Bell et al., 2019b; Röer et al., 2014). Thus, the changing-state effect itself can be conceptualised as arising either from conflict with serial ordering mechanisms or from cumulative involuntary shifts of attention.

Is there a vibrotactile changing-state effect?

Past research on the changing-state effect has almost exclusively employed sound as the changing-state stimuli (for reviews, see Hughes, 2014, 2024; Jones & Macken, 2018). The present study is situated within the contemporary debate on interference in short-term memory, by testing whether vibrations can supply either the serial structure required for process-based interference, or the perceptual salience required for attentional diversion. Accordingly, vibrotactile varying sequences could, in principle, produce disruption through either mechanism: by providing irrelevant serial-structure that interferes with ordering processes (i.e. that competes with vocal–motor sequencing process, not merely introduces perceptual change), or through eliciting repeated orienting responses driven by perceptual change.

Building on this topic, our lab has recently explored whether vibrotactile stimuli, like irrelevant sounds, might also produce a changing-state effect, thus testing whether this form of interference generalises across sensory modalities. In a recent study (Marsh, Vachon, et al., 2024), we reported a novel vibrotactile changing-state effect, suggesting that a sequence of irrelevant, to-be-ignored vibrations can disrupt verbal serial recall, but only when the sequence contains perceptual variation over time. Steady-state sequences consisted of simultaneous vibrations in both hands, whereas changing-state sequences alternated between hands. The vibrotactile changing-state effect has potentially far-reaching theoretical implications for the debate on modality generality in short-term memory, which we discuss in detail below. However, the effect has so far been demonstrated in only one published report (in two experiments). The aim of the present study was to provide the first systematic replication of this effect in the context of serial recall. While Marsh, Vachon, et al. (2024) employed three different memory tasks, we focused exclusively on traditional serial recall, the most widely used and theoretically central measure of short-term memory, and the task in which the strongest effect was initially observed.

Marsh, Vachon, et al.'s (2024) finding was theoretically grounded in earlier work showing that vibrations can interfere with tactile working memory (Bancroft & Servos, 2011), and engage motor systems (Burton et al., 2004; Caetano & Jousmäki, 2006). If passive tactile stimulation engages motor processes, it may in principle compete with the speech-motor rehearsal mechanisms thought to underpin verbal serial recall (e.g. Hughes et al., 2009). Tactile perception also supports streaming (Gallace & Spence, 2011), a perceptual grouping mechanism (e.g. Bregman, 1990) that is essential for producing the changing-state effect (Jones et al., 1992; Jones & Macken, 1995). Across three experiments, Marsh, Vachon, et al. (2024) found that vibrotactile changing-state sequences disrupted performance in both a standard serial recall task (Experiment 1), and a probed order task (Experiment 3), which both require memory for serial order. The effect was not found, however, in a missing item task (Experiment 2), a task that does not require memory for serial order. Taken together, these findings provided preliminary support for the idea that changing-state interference can extend beyond the auditory modality and arise in response to vibrotactile variation – thus reinforcing the core claim of the interference-by-process theories: that serial order information, rather than modality or representational content, drives disruption in short-term memory (Jones & Tremblay, 2000).

Disrupting serial recall with different distractor types

Theoretical progress in this field often involves the use of different types of distractor stimuli to evaluate what kinds of information interfere with memory (Jones & Macken, 2018). For example, Jones and Macken (1993; but see LeCompte et al., 1997) examined the auditory changing-state effect and found that both irrelevant speech (verbal) and irrelevant tones (non-verbal) can disrupt performance in a verbal serial recall task. This finding challenged the original formulation of the Working Memory Model (Baddeley & Hitch, 1974;

Salamé & Baddeley, 1982), which held that only verbal material should disrupt verbal memory. In response, the model was later revised to suggest that disruption depends on whether irrelevant sound is sufficiently speech-like to gain automatic access into the phonological store (Salamé & Baddeley, 1990). However, studies have shown that even sounds dissimilar to speech, such as interrupted pitch glides, can produce interference – so long as they exhibit changing-state information (Jones et al., 1992). The mere fact that such non-speech sounds can impair serial recall suggests that temporal variability, rather than content similarity or speech-likeness, may be the key factor. This provides strong support for interference-by-process accounts, which propose that disruption arises when task-irrelevant stimuli carry serial order information that competes with the serial ordering of the to-be-remembered material imposed via the serial rehearsal process.

The finding of a vibrotactile changing-state effect by Marsh, Vachon, et al. (2024) carries important theoretical implications for models of short-term memory, as it extends the seminal results of Jones and Macken (1993) into the vibrotactile modality, going beyond auditory distraction. A key theoretical contribution of Marsh, Vachon, et al. (2024) was to demonstrate that the distractor sequence need not be auditory to produce a changing-state effect in verbal serial recall. This supports the idea of an amodal workspace in short-term memory (Jones & Macken, 1993; Jones et al., 1995; MacDermid et al., 2023), in which cognitive processes with similar serial order information, rather than similar content, can interfere with one another. Moreover, the fact that irrelevant vibrations disrupted verbal serial recall, despite sharing no phonological or semantic content with the memoranda, challenges content-based accounts of short-term memory (e.g. Cowan, 1999; Neath, 2000; Oberauer et al., 2004; Page & Norris, 2003; Salamé & Baddeley, 1982). Such models typically predict that interference arises only when distractors and targets share representational features, particularly in the same modality. The results of Marsh, Vachon, et al. (2024), therefore, offered an intriguing test case for evaluating the limits of content-based interference and the broader applicability of interference-by-process mechanisms across modalities.

On the interference-by-process theory, the critical "process" refers to the temporal sequencing operations that underpin verbal serial recall. These are typically instantiated in vocal–motor planning routines rather than in modality-specific storage (Hughes et al., 2009; Hughes & Marsh, 2017; Jones & Macken, 2018). This serial ordering mechanism therefore differs from phonological storage, from eye-movement-based spatial rehearsal (e.g. Tremblay et al., 2006), and from attentional refreshing processes invoked in resource-sharing frameworks (Barrouillet & Camos, 2012). Importantly, recent evidence indicates that eye movements do not function as a robust motoric rehearsal device (Souza et al., 2020). This reinforces the view that the relevant process is a speech-motor sequencing routine, not a general oculomotor or attentional mechanism.

Several broader frameworks of short-term memory offer complementary perspectives on how serial information is maintained. Models such as Time-Based Resource Sharing (TBRS; Barrouillet & Camos, 2012) emphasise the allocation of attentional "refreshing" to prevent temporal decay, whereas Serial Order in a Box (SOB; Farrell & Lewandowsky, 2002) characterises serial recall as vulnerable to interference through associative bindings and ordering cues. Notably, extensive work on irrelevant-sound and changing-state effects has ruled out content-based overlap as a viable explanatory mechanism in these paradigms (e.g. Jones & Macken, 1995). Consequently, the core theoretical debate now centres on two alternatives: interference-by-process, where irrelevant serial structure conflicts with the processes underpinning ordered recall, and attentional-capture accounts, which attribute disruption to involuntary orienting toward perceptual change.

Although tactile sequences have been less extensively studied than visual or auditory material, there is clear evidence that tactile events can support short-term, order-sensitive representations. For example, tactile immediate serial recall shows hallmark phenomena of ordered memory such as the Ranschburg effect (Johnson et al., 2019) and priority-based enhancement of selected items (Roe et al., 2024), indicating that tactile sequences can form coherent temporal structures. At the same time, tactile perception is characterised by relatively coarse temporal and spatial resolution (Craig, 1980; Hollins & Bensmaïa, 2007) and by rapid sensory adaptation, whereby repeated vibrotactile stimulation leads to a reduction in perceived intensity and diminished salience (Gescheider et al., 2004; Hollins et al., 1990). These properties suggest that while tactile events can be encoded in short-term memory, vibrotactile distractors may be relatively easy to ignore unless they possess strong, integrated temporal structure. This background clarifies both the potential and the limits of vibrotactile input as a source of distraction in the present experiments.

A further consideration concerns distraction effects that involve spatial variation. In the auditory domain, changing the spatial location of distractors, such as alternating left- and right-ear presentation, does not reliably produce a changing-state effect, because spatial separation can lead to perceptual segregation into multiple steady-state streams rather than a single varying stream (Jones & Macken, 1995; Kattner et al., 2024). Similarly, deviant-sound effects can occur across ears (Vachon et al., 2017), but spatial alternation by itself does not introduce the type of coherent serial structure required for process-based interference. This literature provides a direct analogue to the present vibrotactile design: alternating tactile stimulation across hands may likewise fail to form an integrated changing-state stream, instead being perceived as two independent steady sources. From this perspective, the spatial alternation used by Marsh, Vachon, et al. (2024) or in Experiments 1, 2 and 4 of the present study would not necessarily be expected to evoke a changing-state effect. This spatial-integration constraint is central to evaluating whether vibrotactile variation can, in principle, support the type of perceptual organisation required for serial interference.

Overview of the present experiment series

We report four experiments designed to both replicate and extend the original findings. Experiment 1 was a close partial replication of Marsh, Vachon, et al. (2024; Experiment 1), with a key addition: we manipulated token set size to examine whether a larger number of vibrotactile tokens might accentuate any changing-state effect. This idea was inspired by analogous findings in the auditory domain (Bell et al., 2019a). Experiment 2 explored whether the vibrotactile changing-state effect might emerge in a visual-spatial serial recall task rather than a verbal one, thereby testing the modality-generality of the effect. Next, Experiment 3 implemented a more comprehensive test of vibrotactile interference using a broader range of changing-state sequences, including variations in spatial location, intensity and temporal rhythm, to assess whether more dynamic or richly varying sequences might produce stronger interference effects. Finally, Experiment 4 completed the circle with an exact replication of the first experiment reported in Marsh, Vachon, et al. (2024). Together, these four experiments constitute a rigorous and comprehensive test of the vibrotactile changing-state effect.

To preview the results of the present study, we were unable to replicate the vibrotactile changing-state effect reported by Marsh, Vachon, et al. (2024), across four experiments. These findings run counter to our primary hypothesis and call into question the robustness of the original effect. As such, the goal of this article is to provide a transparent account of this failure to replicate and, in doing so, to contribute to the cumulative and corrective nature of the scientific process. The remainder of this paper presents a full account of the methods and results, followed by a general discussion that places our findings in relation to prior work and outlines their theoretical implications.

Experiment 1

Experiment 1 served as a close partial replication of Marsh, Vachon, et al. (2024; Experiment 1), which reported a vibrotactile changing-state effect in a visual-verbal serial recall task. The aim was to replicate this effect while implementing minor but purposeful adjustments to the original design to better isolate the vibrotactile manipulation. Of most note, we removed the auditory distractor condition used in the original study to focus exclusively on the effects of vibrotactile stimulation. In addition, we introduced a second changing-state condition to increase the degree of temporal and spatial variation in the vibrotactile distractor sequence. This manipulation, comparable to the token set size effect observed in auditory distraction (e.g. Bell et al., 2019a), was intended not to test attentional capture per se, but to evaluate whether greater perceptual variability within a changing-state sequence would magnify any disruption of serial recall. In this design, the steady-state condition (SS) comprised repeated presentations of a single vibrotactile token (simultaneous vibration in both hands), while the two changing-state conditions consisted of sequences alternating between the two (CS2) or three (CS3) distinct tactile configurations (i.e. vibrations alternating predictably across left/right or left/right/both hands). We tested the token set size effect in the tactile modality to evaluate potential functional similarities across auditory and tactile distraction. Our primary hypothesis was that vibrotactile changing-state sequences, particularly those with a larger token set, would lead to a greater disruption of serial recall accuracy than steady-state sequences.

Method

Participants

Forty participants (24 female, 16 male, Mean age = 27.8 years, *SD* = 7.9) took part in Experiment 1. Most were students at Luleå University of Technology who responded to advertisement. Participants received a gift card (99 SEK) as compensation. The study took around 30–40 min to complete. The sample size was based in part on a power analysis using G*Power (Faul et al., 2007), drawing on the effect size from Marsh, Vachon, et al. (2024; Experiment 1), who reported a medium effect (Cohen's $d_z = 0.588$). With $\alpha = .05$ and power (1 − β error probability) set to .80, the estimated minimum required sample was $N = 25$. To ensure sufficient power for this replication attempt, we increased the sample beyond the $N = 30$ used in Marsh, Vachon, et al. (2024), collecting data from 40 participants. Our sample of $N = 40$ was a-posteriori also deemed appropriate by a new power analysis with power (1 – β error probability) set to the more conservative .95, which reduces the risk of false outcomes. All procedures of the experiments complied with the Declaration of Helsinki and were reviewed by the Swedish Research Ethics Authority (Dnr: 2023-07427-01).

Materials, design and procedure

The experiment was created in PsychoPy (version 2024.1.5, Peirce et al., 2019) and run on Windows 10 desktop computers. Displays were 52.5 cm wide and 29.5 cm tall (active screen region). Participants were seated in quiet individual testing booths at Luleå University of Technology. Up to three participants could be tested simultaneously in separate cubicles. Vibrotactile stimuli were delivered via custom-built vibration handles (Figure 1). These handles were the same as those used by Marsh, Vachon, et al. (2024). Each handle consisted of a plastic tube (30 mm diameter, 136 mm length) housing a motor that spun an eccentric mass on a rotor, to generate vibration. The handles were controlled via a parallel port and a central control unit. A button on the top of each handle allowed participants to initiate trials. To minimise sound from the motors, participants wore sound attenuating Sennheiser HD 280 Pro headphones throughout. These headphones delivered no auditory signal but served to attenuate any noise produced by the vibration handles.

Figure 1. A picture of the vibrotactile stimulation device. Handles that would deliver vibrations are shown to the left, and to the right of them is the control unit. Participants would hold the handles during the stimulus phase of the serial recall task.

Following the stimulus parameters of Marsh, Vachon, et al. (2024), the vibrotactile distractors had an amplitude of 2.3 m/s^2 (RMS), a frequency of 33 Hz, and a duration of 250 ms. The chosen frequency (33 Hz) falls within the range commonly used in vibrotactile psychophysics to produce clearly perceptible, suprathreshold stimulation engaging rapidly adapting mechanoreceptors (Gescheider et al., 2004). There were three vibrotactile distractor sequence conditions (illustrated in Figure 2). Two of these replicated those used in Marsh, Vachon, et al. (2024): a steady-state (SS) condition, in which vibrations were simultaneously presented to both hands, and a changing-state 2-token (CS2) condition, in which vibrations predictably alternated between left and right hands. To test whether increased variability in the distractor stream would intensify disruption, we introduced a third condition: a changing-state 3-token (CS3) sequence, consisting of vibrations that predictably alternated across left, right, and both hands. Thus, the SS condition featured one vibrotactile token, while CS2 and CS3 included two and three distinct tokens, respectively. This allowed us to examine whether greater perceptual variation within a changing-state sequence might accentuate disruption. To ensure counterbalancing, CS2 sequences began with left-hand stimulation for half the participants and with right-hand stimulation for the other half (see Figure 2). The six possible orderings of left/right/both in the CS3 condition (e.g. left-right-both, right-both-left, etc.) were distributed evenly across trials and participants (see Figure 2).

Each trial consisted of a visual-verbal serial recall task. Participants were presented with a sequence of eight digits, drawn randomly from 1 to 9, with the constraint that no two consecutive digits could form a simple ascending or descending sequence (i.e. adjacent digits could not differ by ±1). This restriction aimed to prevent chunking strategies based on numerical proximity. Digits were presented one at a time, in the centre of the screen in white Calibri font (against a mid-gray background), with a height of 3.54 cm (12% of the screen's vertical extent). Each digit appeared for 800 ms, followed by a 75 ms "silent" period, a 250 ms vibrotactile stimulus, and another 75 ms "silent" period before the next digit. As in Marsh, Vachon, et al. (2024), digits and vibrations were thus temporally offset ensuring that vibrations did not occur simultaneously with visual onset. Each trial contained eight such stimulus presentation sequences.

Vibrotactile distractor conditions ("states") constituted our first experimental factor (Figure 2). Our

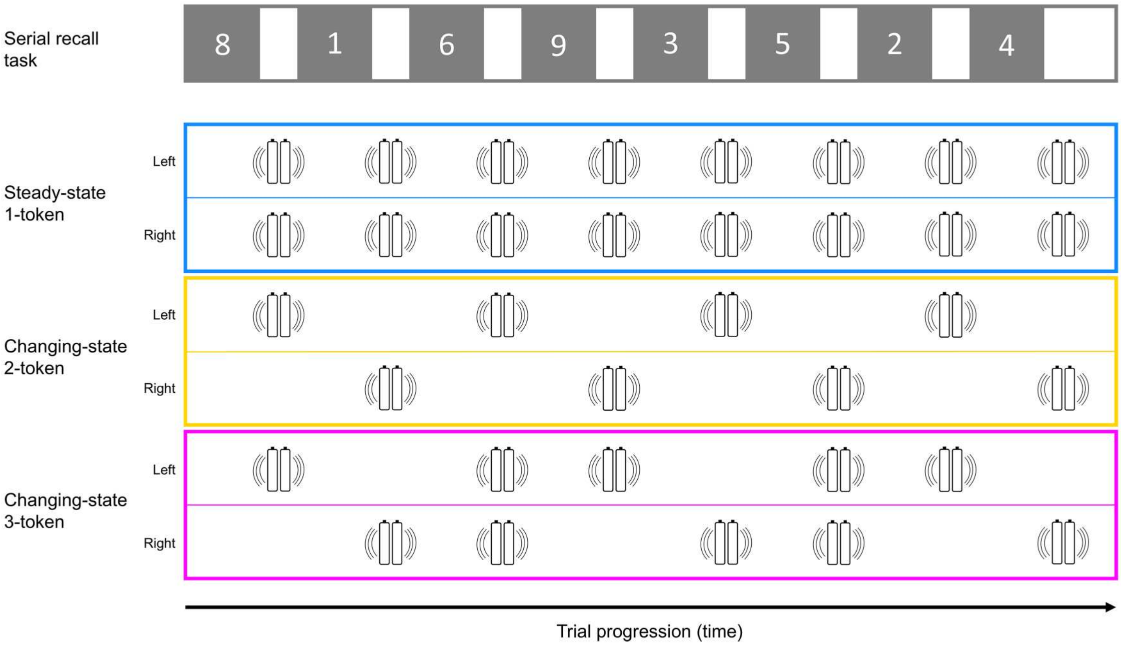

Figure 2. Stimulus structure of a trial in Experiment 1. An example sequence of eight digits in the visual-verbal serial recall task is shown at the top of the figure, below are the three distractor sequence conditions. The steady-state condition consisted of only one token: vibrations in both hands. The two changing-state conditions consisted of either two or three tokens, that alternated across the hands in different patterns. Left and right refers to hand-of-presentation.

second experimental factor was serial position, as participants reconstructed sequences of eight digits in order (see "serial recall task" in Figure 2). Our design was therefore a repeated measures 3 (State: SS, CS2, CS3) × 8 (Serial position: 1, 2, 3, 4, 5, 6, 7, 8) within-participants design.

Participants initiated each trial by pressing a button located on either the left or right vibration handle (randomly assigned). This ensured that both hands were in contact with the handles during stimulus presentation. Immediately after stimulus presentation, participants were instructed (on-screen) to place the handles on the desk and respond using the computer mouse. They were then shown a set of clickable on-screen buttons containing the digits 1–9 and they were asked to reproduce the sequence in the correct order. A string of eight placeholder question marks ("?") tracked response progress: each time a digit was selected, the corresponding placeholder was replaced. A digit could be selected multiple times, but responses were final once entered.

Participants completed two practice trials at the start of the session. These were presented without vibrations, and participants were not required to hold the handles. The main task included 54 experimental trials, with 18 trials per distractor condition (see Figure 2). Trials from the three distractor conditions were presented in a pseudo-random interleaved order, with a restriction that each set of three trials would contain each of the three conditions, in varying orders. This prevented "streaks" where one condition might be repeated many times in a row by chance.

Participants provided their age and gender at the start of the session and confirmed informed consent by button press. They were instructed to focus on the digit sequences and to ignore the vibrations. Pause screens appeared when one-third and two-thirds of the experiment had been completed, allowing for natural breaks. Participants were also free to pause between trials if needed.

Summary of likeness to Marsh, Vachon, et al. (2024)

Experiment 1 closely mirrored Marsh, Vachon, et al. (2024; Experiment 1) in terms of task, apparatus, and distractor stimuli. However, we excluded the quiet and auditory distractor blocks used in the original study and introduced a third changing-state condition (CS3) to manipulate token set size. We also increased the number of vibrotactile trials (from 40 to 54), the number of participants (from 30 to 40), and adjusted stimulus timing (digit duration = 800 ms vs. 1 000 ms in Marsh, Vachon, et al., 2024). Additionally, the digit set was limited to 1–9 (excluding 0), and recall length was reduced from nine to eight digits. These adjustments were made to streamline the task while preserving the essential features relevant to testing the vibrotactile changing-state hypothesis.

Data analysis, availability and transparency

All hypotheses, sample size decisions, experimental design details, measures, and analyses are fully reported in this article. Statistical analyses were conducted using Jamovi (version 2.3.28.0), and JASP (version 0.18.3), with results reported using both frequentist and Bayesian approaches. In the present article, the Bayesian analyses sometimes produced a result of infinite support for a hypothesis (main effects of serial position curves), but in JASP, "$BF_{10} = \infty$" reflects numerical overflow with an extremely large number rather than a literal infinite Bayes factor. Although this study was not preregistered, all data are publicly available via the Open Science Framework (https://doi.org/10.17605/OSF.IO/7JHVU).

In addition to the Bayes factors reported for individual experiments (computed in JASP using default Cauchy priors on standardised effect sizes), we conducted a cross-experiment Bayesian random-effects meta-analysis of the vibrotactile changing-state effect. For this analysis, we modelled the paired mean difference in recall between steady-state and changing-state conditions (SS – CS) for each experiment as normally distributed around a study-specific effect θ_i with known sampling variance based on the observed standard error. The study effects were in turn drawn from a normal population with mean μ and between-study standard deviation τ. We used weakly informative priors, specifying $\mu \sim \text{Normal}(0, 0.1^2)$ and $\tau \sim \text{HalfNormal}(0.05)$. These priors reflect the expectation, based on the broader irrelevant-sound literature, that any vibrotactile changing-state effect is likely to be small in absolute terms, while remaining broad enough to avoid biasing inference strongly toward the null or any particular non-zero effect size. Posterior summaries are reported using 95% highest-density intervals (HDIs), and a Savage–Dickey density ratio was used to quantify Bayes factors for $\mu = 0$ versus $\mu \neq 0$.

Results

Experiment 1 tested whether changing-state vibrotactile sequences (CS2 and CS3) would disrupt verbal serial recall more than steady-state sequences (SS), as reported by Marsh, Vachon, et al. (2024). Responses were scored using a strict serial recall criterion: a digit response was marked correct only if it matched the digit at the same position in the original stimulus sequence. Figure 3 presents the results. Panel A shows mean recall accuracy across the three distractor conditions; Panel B plots serial position curves. Contrary to our primary hypothesis, a 3 (State: SS, CS2, CS3) × 8 (Serial position: 1, 2, 3, 4, 5, 6, 7, 8) repeated measures analysis of variance (ANOVA), using a Greenhouse-Geisser correction, revealed no significant main effect of state, $F(1.93, 75.22) = .41$, $p = .656$, $\eta_p^2 = .010$. A Bayesian ANOVA provided strong support for the null hypothesis, with $BF_{10} = 0.037$, indicating that the null model was approximately 27 times more likely than the alternative. The absence of a main effect of state shows that the three distractor conditions (SS, CS2 and CS3) did not differ. In a more targeted analysis of the changing state effect, we took the average of the CS2 and CS3 conditions and compared this to the SS condition, again finding no difference in recall performance, $t(39) = 0.31$, $p = .756$, $d_z = 0.049$, Mean difference 0.34 (95% confidence interval, −1.85–2.53), $BF_{10} = 0.179$, with the Bayes factor indicating moderate support for the null hypothesis. Thus, there was no indication of a vibrotactile changing-state effect.

As is expected in serial recall tasks, a robust main effect of serial position was observed, $F(3.57, 139.28) = 65.07$, $p < .001$, $\eta_p^2 = .625$, $BF_{10} = 1.177 \times 10^{14}$, reflecting the typical U-shaped serial position curve (Figure 3(B)). However, there was no significant interaction between state and serial position, $F(8.95, 348.92) = 1.04$, $p = .407$, $\eta_p^2 = .026$, $BF_{10} = 0.001$. As shown in Figure 3(B), all three distractor conditions yielded comparable performance across positions.

Discussion

Experiment 1 yielded no evidence for a vibrotactile changing-state effect in visual-verbal serial recall. The Bayesian analysis indicated evidence against the effect. This null result stands in contrast to the findings of Marsh, Vachon, et al. (2024), who reported significant disruption when the sequence of vibrations alternated across hands. Despite using a comparable design, increasing statistical power with a larger sample size, and introducing a more varied distractor condition (CS3), we observed no decrement in performance for either changing-state condition relative to the steady-state baseline.

These results call into question the robustness of the originally reported effect. However, before drawing firm theoretical conclusions, it is important to examine whether this null finding generalises across other tasks and forms of vibrotactile variation. As the next step, in Experiment 2, we implemented a closely matched design but replaced the verbal recall task with a visual-spatial version.

Experiment 2

Experiment 2 was designed to test whether the lack of a vibrotactile changing-state effect in Experiment 1 was

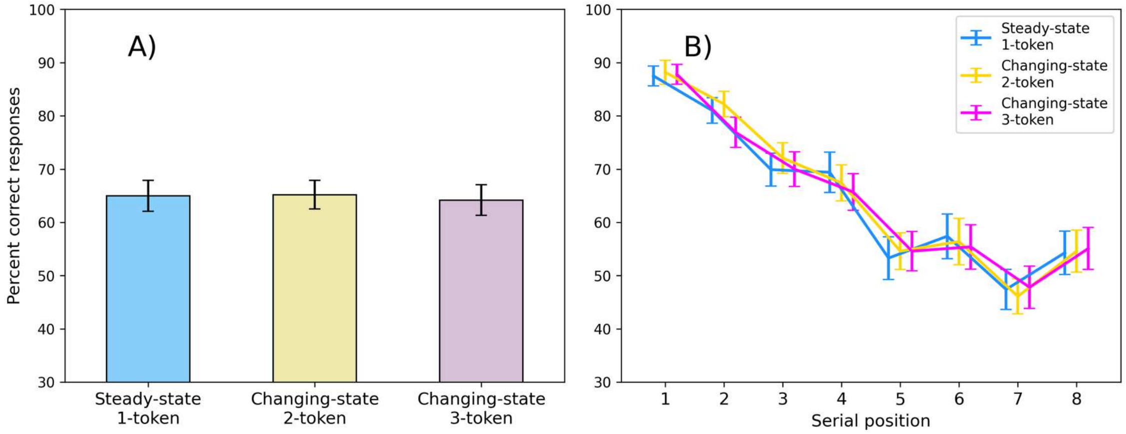

Figure 3. Results of Experiment 1. Panel A shows the aggregate means across all participants, and panel B shows this but split by the serial positions of the responses in each trial (serial position curves). Error bars show the standard errors of the means.

specific to verbal recall, or whether the effect would emerge in the context of visual-spatial memory. To this end, we used the same vibrotactile distractor sequences (see Figure 2) but replaced the visual-verbal serial recall task with a visual-spatial one. Because the distractor sequences varied spatially by alternating between the left and right hands, they might plausibly interfere with a task that also relies on spatial encoding (though in the visual modality). Although auditory changing-state sequences do not disrupt visuo-spatial serial recall (Marsh, Hurlstone, et al., 2024), our vibrotactile sequences differ in that they introduce spatial variation across body locations, which could in principle align more naturally with spatial representations than auditory variation does. We therefore formulated a vibrotactile changing-state hypothesis that visuo-spatial serial recall will be disrupted by spatially alternating vibrations.

Method

Participants

Forty new participants (22 female, 18 male, Mean age = 30.1 years, *SD* = 9.9) were recruited from the campus of Luleå University of Technology. None had taken part in Experiment 1. Our initial estimate of sample size was based on the same procedure as we have reported for Experiment 1. With α = .05 and power (1 − β error probability) set to .80, a sample of *N* = 40 was deemed sufficient to detect a changing-state effect with effect size $d_z = 0.45$. All participants gave informed consent and received a gift card (99 SEK) as compensation. The study took approximately 30–40 min to complete.

Materials, design and procedure

The apparatus, vibrotactile stimuli, and trial structure were identical to Experiment 1, except the task was changed from visual-verbal to visual-spatial serial recall. On each trial, participants viewed a sequence of eight white squares with thin black outlines, each appearing one at a time in distinct locations within a 5 × 5 grid (displayed on a mid-gray background). The grid was 23.6 cm across, centrally positioned on a 29.5 cm tall screen, with participants seated approximately 90 cm from the display. Each square was 1.97 cm in size (1.25° of visual angle), and grid locations were spaced 3.44 cm apart.

Because performance in spatial tasks can be influenced by the properties of the stimulus path – such as the number of path crossings, length, and overall structure (De Lillo et al., 2016; Guerard & Tremblay, 2012; Parmentier et al., 2005, 2006; Parmentier & Andrés, 2006) – we controlled for path difficulty. As these squares appeared in static sequential locations across the screen, they could be mentally characterised by a path, and it is a common strategy for participants to rehearse a sequence of locations as a path-like object. Eighteen unique stimulus paths were created, each comprising eight locations with either one or two crossings. Ten paths had two crossings and eight had one crossing. Total lengths ranged from 14 to 17 grid units. Although path structure is difficult to quantify (De Lillo et al., 2016), all paths were judged by authors to be similarly unstructured. Two additional paths were created for use during practice trials. To ensure that any variability in path difficulty was counterbalanced across distractor conditions, the 18 core paths were mirrored along the horizontal (x) and vertical (y) axes to produce three matched path sets (original, x-mirrored, y-mirrored). One set consisted of the original paths, the second was mirrored about the x-axis (left-right) and the third about the y-axis (top–bottom). See Figure 4 for three examples of stimulus paths, and

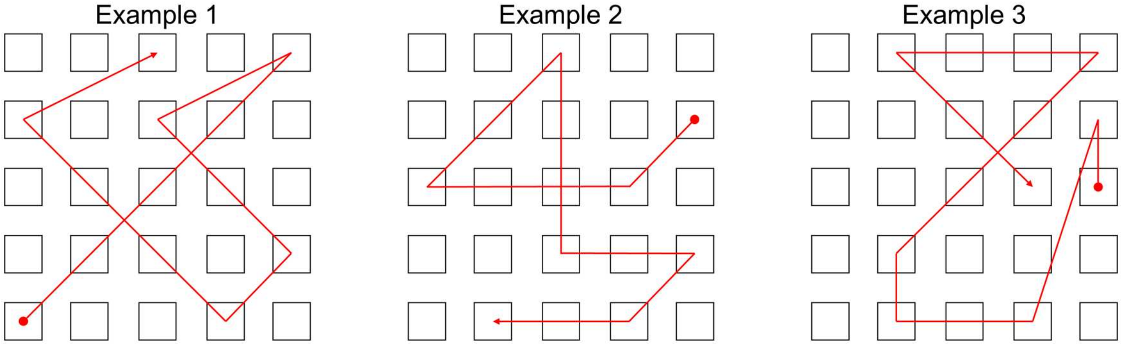

Figure 4. Three example stimulus paths used in the visual-spatial short-term memory task of Experiment 2. Red circle indicates the starting position (first presented stimulus location), connecting lines indicate steps in the path, and the arrow indicates the last location. The squares in the grid are not a scaled representation of the stimulus layout.

Appendix A for a full declaration of the 18 paths used in the current experiment. Each set was assigned to one of the three vibrotactile conditions (SS, CS2, CS3), and the mapping between path set and distractor condition was counterbalanced across participants. This ensured that any incidental differences in path difficulty were distributed evenly across conditions. Within each condition, trial order was randomised. Following each sequence, participants placed the vibration handles down and responded using the mouse. All eight square locations reappeared on the screen simultaneously, and participants clicked the squares in the order they were originally presented. Each clicked square darkened to indicate selection and could not be clicked again. No changes to the response sequence were permitted, and eight clicks were required to complete the trial.

Three vibrotactile distractor conditions (“states”) constituted our first experimental factor. Our second experimental factor was serial position, with eight levels. Our design was therefore a repeated measures 3 (State: SS, CS2, CS3) × 8 (Serial position: 1, 2, 3, 4, 5, 6, 7, 8) within-participants design.

Results

Experiment 2 tested whether vibrotactile changing-state sequences would disrupt visual-spatial serial recall. Participants’ responses were scored according to the strict serial recall criterion: a response was marked correct only if the selected location matched the stimulus at the same position in the original sequence.

Figure 5 shows the results. Panel A displays the average percent correct responses for each distractor condition, and panel B presents these data across serial positions. In contrast to our primary hypothesis, performance was comparable across the steady-state (SS), 2-token changing-state (CS2) and 3-token changing-state (CS3) conditions. A 3 (State: SS, CS2, CS3) × 8 (Serial position: 1, 2, 3, 4, 5, 6, 7, 8) repeated measures ANOVA, adjusted with a Greenhouse-Geisser correction, revealed no significant main effect of state, $F(1.85, 72.16) = .95$, $p = .386$, $\eta_p^2 = .024$, $\mathrm{BF}_{10} = 0.054$. The Bayesian factor indicates that the null hypothesis was 18.6 times more likely than the alternative hypothesis, showing that the three states did not differ. A targeted

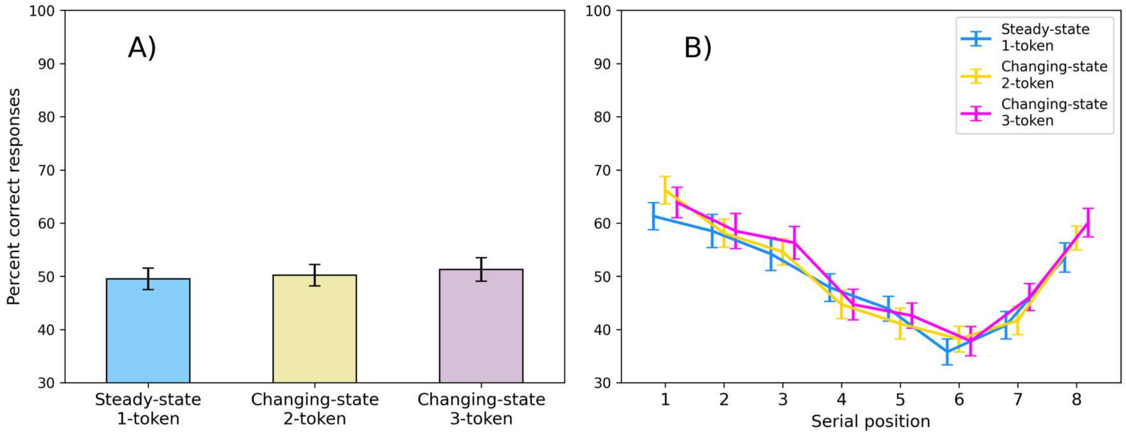

Figure 5. Results of Experiment 2, organised like Figure 3. Error bars show the standard errors of the means.

pair-wise *t*-test compared the SS condition with the average of the CS2 and CS3 conditions, finding no evidence of a vibrotactile changing-state effect, $t(39) = -1.20$, $p = .236$, $d_z = -0.19$, Mean difference −1.26 (95% CI, −3.37–0.86), $\mathrm{BF}_{10} = 0.333$, with the Bayes factor indicating moderate support for the null hypothesis. The expected serial position effect was observed (Figure 5(B)), $F(3.90, 152.13) = 52.47$, $p < .001$, $\eta_p^2 = .574$, $\mathrm{BF}_{10} = \infty$, but there was no significant interaction between distractor condition and serial position, $F(8.70, 339.39) = 1.59$, $p = .119$, $\eta_p^2 = .039$, $\mathrm{BF}_{10} = 0.019$.

After the task, participants were asked to reflect on how the vibrotactile sequences felt in relation to the spatial memory task. Most reported that the vibrations were either not noticed or not particularly distracting. A few noted that the spatially alternating vibrations occasionally felt incongruent with the square movements – for instance, when squares moved left-to-right and vibrations alternated right-to-left. However, these retrospective impressions were not mirrored in the performance data (see Figure 5), and we do not consider them further.

Discussion

Experiment 2 tested whether vibrotactile changing-state sequences would disrupt visual-spatial short-term memory, under the assumption that spatially structured distractors might interfere more readily with a task that relies on spatial encoding. However, as in Experiment 1, the results revealed no evidence of a vibrotactile changing-state effect. Performance was equivalent across the steady-state and changing-state conditions, and Bayesian analyses consistently favoured the null hypothesis, in evidence against the effect. It is important to note that although visuo-spatial serial recall is not reliably disrupted by auditory changing-state sequences (Marsh, Vachon, et al., 2024), it is disrupted by auditory deviation effects (Vachon et al., 2017), which are understood to reflect attentional capture by unexpected events. This distinction clarifies that the task is perfectly capable of detecting external interference arising from attentional diversion, but it does not appear sensitive to the process-based interference mechanism proposed to underlie the changing-state effect. Accordingly, the absence of a vibrotactile changing-state effect in Experiment 2 is unlikely to reflect insensitivity of the visuo-spatial task, but rather fits with broader evidence that the changing-state effect does not generalise to visuo-spatial memory.

Collectively, these considerations highlight that Experiment 2 provided a strong test of whether vibrotactile changing-state patterns could interfere with spatial memory. The null effect observed here aligns with Marsh, Hurlstone, et al. (2024), who similarly found that changing-state auditory sequences do not disrupt visuo-spatial serial recall, reinforcing the view that changing-state interference may be constrained to tasks supported by verbal serial-order processes. If such interference were possible, then it should have been observable here. The main hypothesis was therefore not supported, as indicated by the absence of any performance decrement in response to spatially alternating vibrotactile sequences relative to steady-state sequences. To our knowledge, this is the first study to test the impact of changing-state vibrotactile distractors on a visual-spatial serial recall task. Models of short-term memory often assume that interference is modality-specific – such that spatial distractors are most likely to disrupt spatial memory (Baddeley, 1986). From this perspective, one might have expected the spatially alternating vibration sequences to interfere with the encoding or rehearsal of location-based sequences. However, the results suggest that passively received spatial vibrations do not register as effective distractors in a visual-spatial memory task, at least not in the form used here.

One interpretation is that vibrotactile changing-state effects do not arise when the to-be-remembered material is not encoded within the same sensory modality – that is, when serial memory operates on visual or spatial rather than tactile representations. According to this view, tactile distractors may only be disruptive when the primary task also draws on tactile processing (Roe et al., 2024). While this remains a possibility, we hesitate to draw firm conclusions at this stage (see General Discussion).

An alternative explanation concerns the perceptual organisation of the distractor sequences. Although our design followed the parameters used in Marsh, Vachon, et al. (2024), we were concerned that the spatial alternation of vibrations may not have supported streaming – a process thought to be critical for the changing-state effect. Prior work has shown that changing-state effects in the auditory modality are reduced when alternating tokens are spatially separated. For instance, Jones and Macken (1995; see also Kattner et al., 2024) demonstrated that alternating speech tokens produce less disruption when presented from distinct spatial sources because they are perceived as multiple steady-state streams rather than a single changing-state stream. By analogy, it is possible that the vibrations delivered to the left and right hands in our study were not perceptually integrated into a single stream, but instead registered as two separate steady-state sources, one per hand. If so, this would undermine the serial perceptual organisation needed for a changing-state effect. Marsh, Vachon, et al. (2024) assumed that tactile alternation across the hands would support perceptual streaming, but they also acknowledged that this might not always occur, especially when vibrations are spatially segregated and delivered in rapid succession. Consistent with this, Lin and Kashino (2012) observed that tactile streaming can be limited when stimuli are presented to separate body locations.

Taken together, the present findings and their prior evidence suggest that vibrotactile streaming may not be reliably elicited by spatial alternation alone, at least not under the parameters used here. To address this possibility directly, Experiment 3 introduced a broader range of vibrotactile distractor sequences, including variations in spatial location, intensity, and temporal rhythm, in order to test whether more complex or richly varying patterns might elicit stronger interference effects.

Experiment 3

The results of Experiments 1 and 2 provided no evidence that vibrotactile changing-state sequences disrupt verbal or spatial serial recall. One potential explanation, raised in previous discussion, is that the spatial alternation of vibrations across the hands may not have been perceptually integrated into a single changing-state stream. Without such integration – or streaming – the sequences may have failed to convey irrelevant serial order information in a form that could interfere with the ordered representation of to-be-remembered items.

To address this concern, Experiment 3 broadened the scope of our investigation by introducing a more diverse set of vibrotactile distractor sequences. Specifically, we manipulated not only the spatial location of vibrations (left, right, both hands), but also their intensity (strong vs. weak) and temporal rhythm (regular vs. irregular onset timing). These manipulations were intended to increase the perceptual variability of the distractor sequences, both within and across trials, to determine whether more dynamic and richly varying vibrotactile streams might produce greater interference.

The design included three steady-state conditions (each with a constant setting for one feature: spatial location, intensity, or rhythm) and seven changing-state conditions, which introduced variation in one, two, or all three of these features. In total, ten vibrotactile conditions were tested using the same visual-verbal serial recall task as in Experiment 1. We doubled the number of distractor events per trial, increasing the overall amount of stimulation and the chance that serial patterns in the distractors would engage perceptual processes.

If the absence of a vibrotactile changing-state effect in Experiments 1 and 2 reflects a limitation of perceptual integration, then sequences that vary along multiple perceptual dimensions, and are more likely to be perceived as more salient and more dynamic, may elicit greater disruption. On the other hand, if the results of Experiments 1 and 2 genuinely reflect a broader failure of vibrotactile changing-state sequences to interfere with serial memory, then no pattern of variation, regardless of richness, should produce reliable disruption. Experiment 3 was designed to test these possibilities directly.

Method

Participants

Forty-eight participants were recruited from the campus of Luleå University of Technology. A small number of participants had previously taken part in either Experiment 1 or 2. Participants were compensated with a gift card worth 99 SEK for approximately 60 min of participation. Two participants were excluded from analysis: One due to a computer error and another who chose to withdraw from the study. This left a final sample of 46 participants for analysis (28 female, 17 male, 1 did not report their gender, Mean age = 28.4 years, *SD* = 8.1).

The target sample size exceeded that used in Experiments 1 and 2 (both $N = 40$) in order to increase statistical power and to ensure sufficient data coverage across the ten distractor conditions. We made the a-posteriori determination that a sample of $N = 46$, with $\alpha = .05$ and power ($1 - \beta$ error probability) set to .80, was sufficient to detect a changing-state effect with effect size $d_z = 0.42$.

Materials, design and procedure

The materials, design, and procedure were similar to those of Experiment 1 unless otherwise noted. The vibrotactile distractor sequences differed in two main ways. First, each digit was accompanied by two vibrations (instead of one), resulting in 16 vibrations per trial. Each vibration lasted 250 ms, spaced at 600 ms intervals. One vibration occurred 275 ms after digit onset, overlapping with digit presentation. This increase in vibrotactile stimulation was designed to address concerns that earlier sequences may have been perceptually understimulating.

Second, we introduced ten vibrotactile distractor conditions by manipulating three parameters: intensity (strength), temporal rhythm (onset timing), and spatial location (hand), along with combinations of these (see Table 1). For each parameter, we created both a steady-state condition (property constant throughout) and a changing-state condition (property varied across items). For example, intensity sequences either remained strong throughout (Level 2) or alternated between weak (2.3 m/s^2 at 33 Hz, Level 1) and strong (61 m/s^2 at 114 Hz, Level 2). Temporal rhythm was either fixed (600 ms) or jittered by ±100–250 ms for the first vibration per digit (second vibration was fixed). Spatial location was either constant (both hands) or alternating (left/right).

In total, three one-way, three two-way, and one three-way changing-state conditions were tested, along with three steady-state counterparts. In all changing-state conditions, the order of token features was randomised rather than fixed (cf. Figure 2), reducing predictability compared to Experiments 1 and 2. Each condition appeared in 10 trials (100 total trials), presented in a pseudo-random order: all ten conditions were each presented in a random order before any conditions repeated.

To summarise our design, the ten vibrotactile distractor conditions (Table 1) constituted the first experimental factor. The second experimental factor was serial position, with eight levels. The design was therefore a repeated measures 10 (Condition: SS intensity, SS temporal, SS spatial, CS intensity, CS temporal, CS spatial, CS intensity AND temporal, CS intensity AND spatial, CS temporal AND spatial, CS intensity AND temporal AND spatial) × 8 (Serial position: 1, 2, 3, 4, 5, 6, 7, 8) within-participants design.

Table 1. Overview of stimulus parameters in the ten conditions of Experiment 3.

Condition	Intensity (strength level)	Temporal (rhythm)	Spatial (hand-of-presentation)
One-way			
SS intensity	**2**	Steady	Both
SS temporal	1	Steady	Both
SS spatial	1	Steady	**One (left OR right)**
CS intensity	**Alternating (1–2)**	Steady	Both
CS temporal	1	**Unsteady**	Both
CS spatial	1	Steady	**Alternating (left-right)**
Two-way			
CS intensity AND temporal	**Alternating (1–2)**	**Unsteady**	Both
CS intensity AND spatial	**Alternating (1–2)**	Steady	**Alternating (left-right)**
CS temporal AND spatial	1	**Unsteady**	**Alternating (left-right)**
Three-way			
CS intensity AND temporal AND spatial	**Alternating (1–2)**	**Unsteady**	**Alternating (left-right)**

Note: Bold indicates a change from a baseline steady-state stimulus setting. SS = steady-state, CS = changing-state. One-, two-, or three-way indicates how many stimulus settings were changed at once.

Results

Results for Experiment 3 are shown in Figure 6. Despite using vibrotactile changing-state sequences that varied in spatial location, intensity, and temporal rhythm – alone and in combination – there was no evidence of a vibrotactile changing-state effect. That is, none of the changing-state conditions produced significantly lower recall accuracy than their steady-state counterparts. Bayesian analyses consistently favoured the null hypothesis.

To formally test this, we compared the six one-way conditions (Table 1) in a repeated measures 2 (State: steady, changing) × 3 (Stimulus parameter: intensity, temporal, spatial) × 8 (Serial position: 1, 2, 3, 4, 5, 6, 7, 8) ANOVA, adjusted with a Greenhouse-Geisser correction. This analysis focuses on comparing the three one-way steady-state conditions (blue bars in Figure 6) with the three one-way changing-state conditions (yellow bars in Figure 6). As shown in Figure 6, there was no main effect of state, $F(1, 45) = .273$, $p = .604$, $\eta_p^2 = .006$, and the Bayes factor strongly favoured the null, $BF_{10} = 0.041$. This suggests that data were approximately 24 times more likely under the null hypothesis than under the alternative. There was a robust effect of serial position, $F(3.16, 141.98) = 53.394$, $p < .001$, $\eta_p^2 = .543$, $BF_{10} = \infty$, consistent with the typical serial position curve (Figure 7). However, there was no main effect of stimulus parameter, $F < 1$, $BF_{10} = 0.013$, indicating that distraction did not differ by feature (spatial, intensity, or temporal; Figure 7). No significant two-way interactions were found (all $F < 1$). A significant three-way interaction emerged, $F(9.52, 428.51) = 2.21$, $p = .018$, $\eta_p^2 = .047$, but the corresponding Bayes factor ($BF_{10} = 1.875 \times 10^{-8}$) provided extreme support for the null hypothesis. Given its small effect size, lack of theoretical coherence, and absence of support from the Bayesian analysis, we do not interpret this interaction further.

The above omnibus ANOVA included six out of ten distractor conditions in a scoping analysis that focused on the one-way steady- and changing-state conditions and their serial position curves (Figure 7). In a more targeted analysis of the changing-state effect, we took the average of the three steady-state conditions (spatial, intensity, and temporal) and compared this to each of the seven changing-state conditions in seven pair-wise *t*-tests. That is, we compared the average of the three left-most bars in Figure 6 with each of the other bars. There were no significant differences in any of the seven comparisons (all $p > .05$, and all BF_{10}'s were in the range 0.162–0.427, consistently favouring the null hypothesis with moderate or anecdotal evidence).

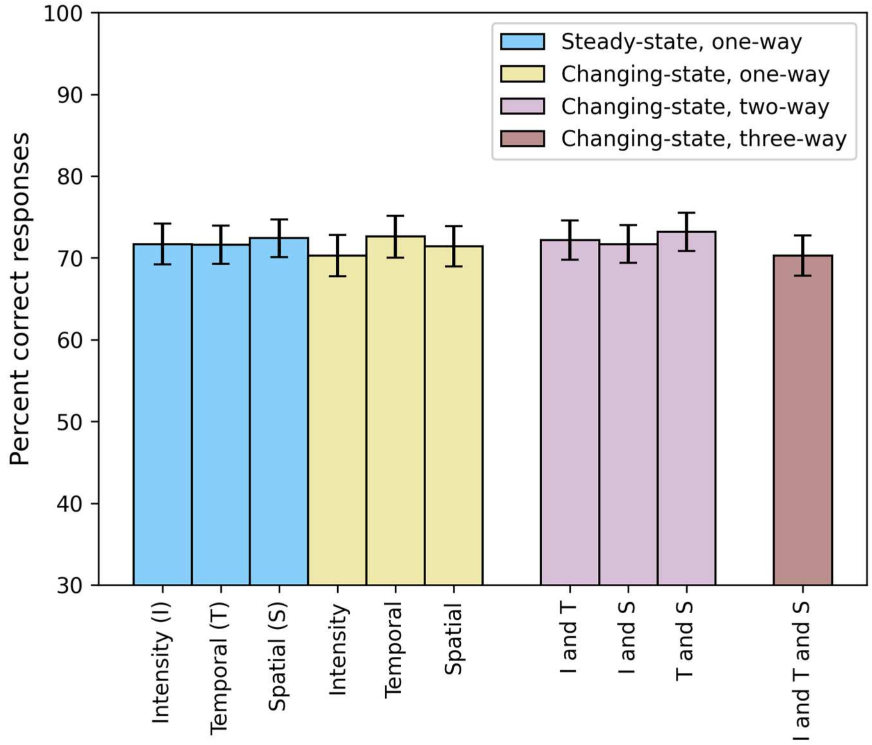

Figure 6. Results of Experiment 3. There is one bar for each of the ten distractor conditions, explained in Table 1. The "Intensity" (I) condition reflects that vibrations were always stronger (steady-state) or changed in strength (changing-state). The "Temporal" (T) condition reflects that vibrations had either a steady rhythm (steady-state) or a broken rhythm (changing-state). The "Spatial" (S) condition reflects that vibrations were always presented in both hands (steady-state) or in alternating hands (changing-state). Changing-state stimulus parameters were also presented in combination-conditions (the four right-most bars; see Table 1). Errors bars show the standard errors of the means.

Discussion

Experiment 3 was designed to test whether the vibrotactile changing-state effect might emerge under more perceptually stimulating conditions. To that end, we introduced ten vibrotactile distractor sequences varying in spatial location, vibration intensity, and temporal rhythm, either individually or in combination. We also doubled the number of vibration events per trial to ensure stronger stimulation and greater opportunity for distractor patterns to interfere with serial memory. Despite these enhancements in tactile stimulation, we again found no evidence of a vibrotactile changing-state effect, with Bayesian analyses favouring the null hypothesis.

This failure to replicate the effect across multiple forms of perceptual variation suggests that changes in a single feature (spatial, intensity, or temporal) or even multiple features in combination do not suffice to disrupt visual-verbal serial recall. These results run counter to the hypothesis that perceptual variability alone, regardless of modality, can interfere with the seriation process, as proposed by the interference-by-process account (Jones & Tremblay, 2000). The results also challenge attentional capture views (Cowan, 1995) as these salient and varied vibrations did not appear to cause "mini-deviants", eliciting repeated orienting responses (Bell et al., 2019b; Röer et al., 2014), which would be expected to disrupt serial recall.

One possibility for this is that, unlike auditory stimuli, vibrotactile sequences may not readily support perceptual streaming in a way that promotes the processing of change. In the auditory domain, changing-state sequences rely on perceptual grouping and the detection of variation within a coherent stream (Jones et al., 1992). In the tactile domain, however, vibrotactile inputs may not be perceptually integrated into a single dynamic sequence. As noted earlier, there are limitations to tactile streaming, particularly when vibrations are spatially segregated across the body (Lin & Kashino, 2012). This may undermine the formation of a unified distractor stream necessary for producing changing-state effects. Experiment 3 suggests that this might be the case, also for vibrotactile sequences that change in intensity (strength) and onset timing (rhythm).

Another potential explanation concerns modality-specific differences in how sequences are perceptually organised and processed. Auditory input, by its nature,

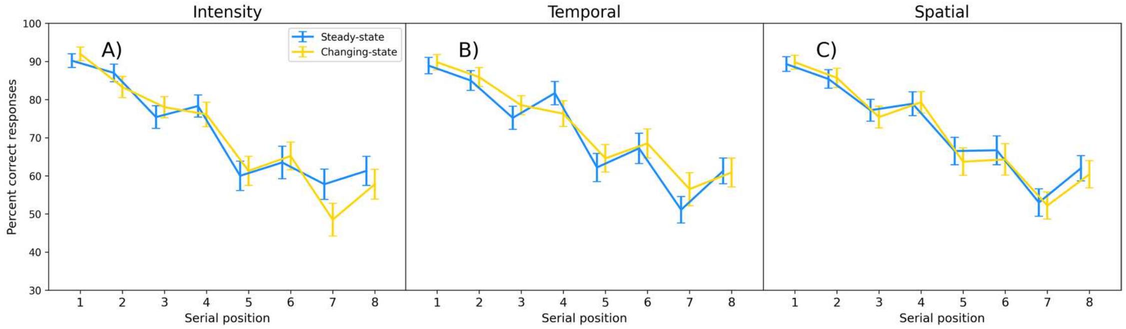

Figure 7. Serial position curves from the six one-way conditions in Experiment 3. See Table 1 for details. Errors bars show the standard errors of the means.

lends itself to structured, temporally unfolding patterns that may intrude upon the serial ordering mechanisms of short-term memory, particularly those supporting speech-motor planning and rehearsal (e.g. Hughes et al., 2009). In contrast, vibrotactile sequences may not engage comparable perceptual structuring or dynamic grouping processes (cf. Lin & Kashino, 2012) thereby limiting their potential to interfere with serial memory. From this perspective, it is not merely the presence of variation that matters, but whether that variation is organised in a way that aligns with and disrupts the serial processes involved in the task.

Taken together with the results from Experiments 1 and 2, the findings from Experiment 3 suggest that changing-state interference may not readily generalise to the tactile modality. Despite extensive efforts to enhance perceptual variation and induce distractor streaming, no reliable interference was observed. While no objective interference emerged in Experiment 3, it is worth noting that participants frequently reported that some vibration sequences felt more distracting than others, a subjective impression also noted by lab members during piloting. These reports, however, were not accompanied by measurable performance costs (see Figure 6), and as such, we do not interpret them as meaningful indicators of distraction. Next, as a final empirical step in the present study, we conducted a direct replication of the first experiment of Marsh, Vachon, et al. (2024) to better understand the possible explanations for the discrepancies in outcomes across the articles.

Experiment 4

So far, the present study has found no evidence for the vibrotactile changing-state effect, first reported in Marsh, Vachon, et al. (2024). However, our first three experiments have only been conceptual replications of the effect. In Experiment 4, we therefore sought to replicate the exact design of Marsh et al.'s first experiment. We were concerned that some methodological difference, however minor, between our experiments and Marsh et al.'s underpinned the discrepancy in outcomes. For example, we have used eight to-be-recalled digits instead of nine, our presentation rate was slightly faster (800 ms per digit vs. 1 000 ms in Marsh et al.), and we did not use any blocks that lacked tactile distraction. It thus remains possible that the vibrotactile changing-state effect depends on some specific boundary conditions, for example having a higher cognitive burden (longer memory task) or variety in stimulation (auditory and quiet blocks, in addition to tactile). Experiment 4 has the potential to reveal whether the vibrotactile changing-state effect is subject to some specific boundary conditions present in the design of Marsh, Vachon, et al. (2024; Experiment 1), or, alternatively, a failure to replicate the effect here would suggest that the previous 2024 report was based on a false positive result.

Method

Participants

Thirty participants (17 female, 13 male, Mean age = 36.6 years, *SD* = 15.7) were recruited from the campus of Luleå University of Technology. They received a gift card worth 99 SEK for approximately 60 min of participation. In this methodologically exact replication, we used the same sample size of $N = 30$ that Marsh, Vachon, et al. (2024) had previously used in their first experiment to obtain a significant vibrotactile changing-state effect (with $d_z = 0.588$). This sample was estimated to have sufficient power, as an a priori power analysis showed the minimum required sample was $N = 25$, with $\alpha = .05$ and power ($1 - \beta$ error probability) set to .80. We intentionally matched the original sample size to conduct a methodologically exact replication before extending sample size. This design isolates procedural similarities rather than statistical ones.

Materials, design and procedure

We took several steps to match the method used by Marsh, Vachon, et al. (2024) in their first experiment. The laboratory apparatus and the vibrotactile stimulus material were identical to that previously described for our Experiment 1. The vibration handles were the same pairs of handles as those used by Marsh, Vachon, et al. (2024). We introduced auditory distractor stimuli; letter tokens “a” and “b” were recorded by a male voice at an approximately even pitch. These sound files were created in Audacity where they were normalised in peak amplitude and edited to a duration of 250 ms and saved at 16-bit resolution with a sampling rate of 44.1 kHz. In the experiment, these auditory tokens were heard at approximately 65 dB(A) in the noise attenuating headsets.

Following the blocked design of Marsh, Vachon, et al. (2024; Experiment 1), we used five blocks which constituted three distractor conditions. There were two vibrotactile distractor blocks and two auditory distractor blocks. Each of these blocks constituted 20 trials (10 steady-state and 10 changing-state, randomly mixed within a block). There was also one “quiet” block with 10 trials where there were no distractors. The three distractor conditions were thus vibrotactile, auditory, and quiet, and the total number of trials was 90. Half of all participants began with the two vibrotactile blocks, and ended with the two auditory blocks, and the other half of all participants encountered the opposite order. The quiet block was always the middle block. Participants were notified when a new block was about to begin, affording a natural break.

Like in Experiment 1, a to-be-recalled digit was followed by a to-be-ignored stimulus. In the vibrotactile steady-state condition, vibrations were always presented to both hands simultaneously. In the vibrotactile changing-state condition, vibrations were presented to predictably alternating hands (left/right hand starting point was counterbalanced across participants). In the auditory steady-state condition, sound “a” or “b” were presented in an unchanging sequence (sequences of nine a’s or nine b’s were counterbalanced across participants). In the auditory changing-state condition, sound sequences alternated predictably between “a” and “b” (“a” or “b” starting point was counterbalanced across participants). In the quiet condition, there was no to-be-ignored stimulus. Participants wore the headset and held the handles during all trials.

Each to-be-recalled digit stimulus was presented for 1 000 ms. The digit set was 0–9 and the serial recall task was nine digits long. Except for what has been noted above, all other methodological details were identical to our Experiment 1.

In summary of our design, five conditions that determined the to-be-ignored stimulus constituted our first experimental factor. Our second experimental factor was serial position, with nine levels. Our design was therefore a repeated measures 5 (Condition: vibrotactile steady-state, vibrotactile changing-state, quiet, auditory steady-state, auditory changing-state) × 9 (Serial position: 1, 2, 3, 4, 5, 6, 7, 8, 9) within-participants design.

Results

The results of Experiment 4 are visualised in Figure 8. Of primary interest, there was no vibrotactile changing-state effect, as shown by a non-significant paired-samples *t*-test comparing the vibrotactile conditions, $t(29) = 0.88$, $p = .385$, $d_z = 0.161$, Mean difference 1.28 (95% CI, −1.68–4.24), $\mathrm{BF}_{10} = 0.278$, with the Bayes factor indicating moderate support for the null hypothesis.

In an examination of the full results (Figure 8(B)), a 5 (Condition: vibrotactile steady-state, vibrotactile changing-state, quiet, auditory steady-state, auditory changing-state) × 9 (Serial position: 1, 2, 3, 4, 5, 6, 7, 8, 9) repeated measures ANOVA found a significant main effect of condition, $F(4,\ 116) = 3.84$, $p = .006$, $\eta_p^2 = .117$, $\mathrm{BF}_{10} = 1.635$. The Bayesian factor indicates anecdotal evidence that the conditions differed. The typical serial position effect was observed, $F(8,\ 232) = 81.32$, $p < .001$, $\eta_p^2 = .737$, $\mathrm{BF}_{10} = \infty$, but there was no significant interaction between the distractor conditions and serial positions, $F(32,\ 928) = 1.09$, $p = .339$, $\eta_p^2 = .036$, $\mathrm{BF}_{10} = 0.007$.

The main effect across the five distractor conditions motivates a closer inspection of how these conditions differed. As mentioned above, there was no vibrotactile changing-state effect. There was also, surprisingly, no significant auditory changing-state effect, $t(29) = 0.57$, $p = .575$, $d_z = 0.103$, Mean difference 0.69 (95% CI, −1.79–3.16), $\mathrm{BF}_{10} = 0.225$, with the Bayes factor indicating moderate support for the null hypothesis. Performance in the conditions with distractor stimuli was slightly lower than in the quiet condition, which used no distractor stimulus (Figure 8). We conducted four Holm–Bonferroni-corrected post-hoc comparisons to investigate which conditions significantly differed from the quiet condition: Both auditory conditions significantly differed from the quiet condition ($p < .05$) but the two vibrotactile conditions did not ($p > .05$). In sum, Experiment 4 found no evidence of vibrotactile distraction but auditory distraction was observed in both the steady- and changing-state forms.

To assess whether susceptibility to auditory distraction predicted susceptibility to vibrotactile distraction, we examined the correlation between the auditory and tactile changing-state difference scores (steady-

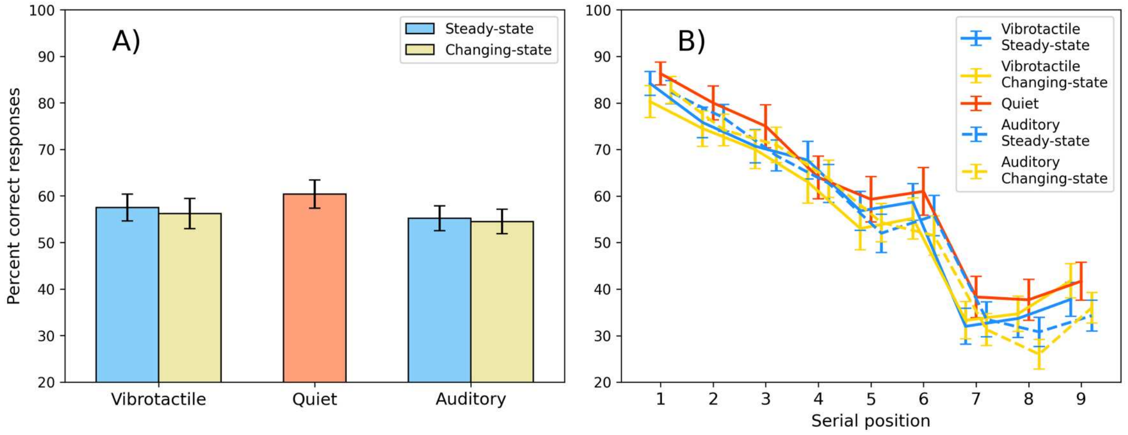

Figure 8. Results of Experiment 4. Panel A shows the mean results for the five distractor conditions, and panel B shows their serial position curves. Error bars show the standard errors of the means.

state minus changing-state). The correlation was near zero, $r(28) = .049$, $p = .796$, indicating no evidence for a shared underlying mechanism. Finally, to examine whether block order influenced the presence of changing-state effects, we conducted a mixed ANOVA including Block Order (auditory-first vs. tactile-first) and Condition (steady-state vs. changing-state). The Block Order × Modality × State interaction was negligible, $F(1, 28) = 3.9 \times 10^{-4}$, $p = .984$, $\eta_p^2 < .001$, indicating that block order did not modulate any changing-state effects.

Discussion

Experiment 4 was an exact replication of Marsh, Vachon, et al.'s (2024) first experiment. Contrary to the previous 2024 report, we found no evidence for a vibrotactile changing-state effect. This, taken together with the first three experiments of the present paper, suggests that there is no robust vibrotactile changing-state effect and that the previous 2024 report was likely based on a false positive result, owing to sampling error. Importantly, both auditory distractor conditions produced reliable impairment relative to quiet, confirming that the task and apparatus were sensitive to auditory distraction. The absence of an incremental changing-state cost therefore does not indicate a failure of the manipulation. The evidential weight behind the auditory changing-state effects spans several decades and laboratories, whereas the vibrotactile changing-state effect rests on a single initial report. Accordingly, a null replication has very different implications across these cases.

Cross-experiment analysis

Directional consistency

Although none of the four experiments revealed a reliable vibrotactile changing-state effect at the group level, it remained possible that a subset of participants consistently showed a distraction cost. To test this possibility, we computed individual difference scores for each participant (steady-state minus changing-state; positive values indicate poorer performance under changing-state stimulation). For experiments with multiple steady- or changing-state conditions (Experiments 1–3), these were averaged to produce a single steady-state and changing-state score per participant.

Bayesian sign tests were then used to determine whether the proportion of positive scores reliably exceeded chance (0.50). Across all four experiments, the distributions were consistent with random variability around zero. In Experiment 1, 23 of the 40 participants (57.5%) showed a positive difference score, indicating slightly poorer performance under changing-state stimulation, while 17 participants (42.5%) showed the opposite pattern. A Bayesian sign test favoured the null hypothesis, $BF_{01} = 3.31$, indicating moderate evidence that the proportion of positive scores did not reliably exceed chance. Here, we report Bayes factors as BF_{01} to reflect that we now expected null effects to dominate the outcomes. In Experiment 2, the distribution was similarly balanced: 17 of 39 participants (43.6%) performed worse in the changing-state condition, whereas 22 (56.4%) showed better performance under changing-state stimulation. Results were tied for one participant, whose data was not included in the sign test as it was neither positive nor negative. The Bayesian sign test again supported the null, $BF_{01} = 3.71$, indicating moderate evidence for no systematic directional bias. A comparable pattern emerged in Experiment 3, where 20 of 45 participants (44.4%) showed a nominal changing-state cost and 25 participants (55.6%) showed the reverse pattern. Results were tied for one participant. Here too, the Bayesian sign test favoured the null hypothesis, $BF_{01} = 4.14$, showing moderate evidence for the data representing random variation around zero. Finally, in Experiment 4, which was an exact replication of Marsh, Vachon, et al.'s (2024) original study, 16 of the 28 participants (57.1%) showed a positive tactile difference score, while 12 participants (42.9%) showed a negative one. Results were tied for two participants. The Bayesian sign test once again provided moderate support for the null, $BF_{01} = 3.29$, indicating no reliable directional preference.

Across all experiments, therefore, there was no evidence that a consistent subgroup of participants exhibited a vibrotactile changing-state cost. Instead, the pattern of individual effects was indistinguishable from random noise, with moderate evidence for the null in every case. Given the consistent absence of directional bias at both the group and participant levels, we next aggregated evidence across seven available experiments using a Bayesian random-effects meta-analysis.

Meta-analytic summary

To quantify the overall evidence for a vibrotactile changing-state effect across all available studies, we conducted a Bayesian random-effects meta-analysis on the paired mean differences in recall between steady-state and changing-state vibration (SS – CS) from seven experiments. In addition to the six published experiments (two from Marsh, Vachon, et al., 2024, and the four reported in this article), we included one further dataset from a study that is publicly accessible via the Swedish repository *Digitala vetenskapliga arkivet* (Digital Academic Archive, DiVA) but not published in peer-reviewed form (Johansson & Tuneström, 2025). This study was conducted in the same laboratory under the same supervisory framework as the experiments reported here and used an identical visual-verbal serial recall task, with vibrotactile steady-state and changing-state distractors. The apparatus, vibrotactile parameters, and task structure mirrored those used in both Marsh, Vachon, et al. (2024) and the present experiments. In this thesis study, the changing-state manipulation consisted of a cyclic sequence of vibrotactile pulses of three different durations (200, 300, and 400 ms), presented with fixed 275-ms pauses and constant amplitude and frequency (2.3 m/s^2, 33 Hz) across all states. This temporal-variation sequence closely matches the temporal changing-state manipulations used in the current study and therefore met inclusion criteria for the meta-analysis. We extracted recall accuracy from steady-state (mean = 70%, SD = 16.3%) and changing-state (mean = 70.7%, SD = 16.2%) conditions, and *t*-statistics from the thesis dataset to derive effect sizes and sampling variances, $t(29) = -0.49$, $d_z = -0.089$. Because the study met all methodological criteria for inclusion and helped avoid publication bias, it was entered into the meta-analysis alongside the other six experiments.

A summary of the meta-analysis is seen in Figure 9. Observed effects were uniformly small (Cohen's d_z range: −0.19–0.59, median = 0.09). The posterior for the overall mean difference indicated only a negligible pooled effect, $\mu = 0.009$, 95% highest-density interval (HDI) [−0.010, 0.028]. Expressed in standardised units using the pooled SD of the difference scores, this corresponds to a pooled Cohen's $d_z = 0.09$, 95% HDI [−0.11, 0.30], and Hedges' $g = 0.09$, 95% HDI [−0.11, 0.30]. Between-study heterogeneity was modest, $\tau = 0.019$, 95% HDI [0.005, 0.044], indicating only minor variation in effects across experiments. A Savage–Dickey Bayes factor comparing a model with a non-zero overall effect (prior $\mu \sim \text{Normal}(0, 0.1^2)$) against a point-null model ($\mu = 0$) favoured the null, $BF_{01} = 6.79$ ($BF_{10} = 0.15$), providing moderate evidence that vibrotactile changing-state sequences do not reliably impair serial recall performance. Although the posterior placed somewhat more mass above zero, $P(\mu > 0 \mid \text{data}) = .86$, the credible interval encompassed both small positive and small negative effects, implying that any true effect is at most trivial in size. Directionally, five of the seven experiments (71%) yielded positive mean differences (SS > CS) and two yielded negative differences (CS > SS). A Bayesian sign test with a uniform prior on the probability of a positive effect was inconclusive, $BF_{01} = 1.31$, indicating that this pattern of signs is compatible with chance variability around zero. Taken together, the meta-analytic evidence suggests that, unlike the typically robust auditory changing-state effect, the vibrotactile analogue does not produce a replicable decrement in serial recall performance.

General discussion

The present study set out to replicate and extend the vibrotactile changing-state effect reported by Marsh, Vachon, et al. (2024), which suggested that irrelevant sequences of alternating vibrations can disrupt visual-verbal serial recall, in line with the interference-by-process account of distraction (Jones & Tremblay, 2000; Linklater et al., 2024; Marsh et al., 2009). Across four experiments, we found no evidence for such an effect – regardless of whether the to-be-remembered material was verbal or spatial, and regardless of whether vibrotactile distractors varied in location, intensity, rhythm, or some combination thereof. Bayesian analyses consistently favoured the null hypothesis.

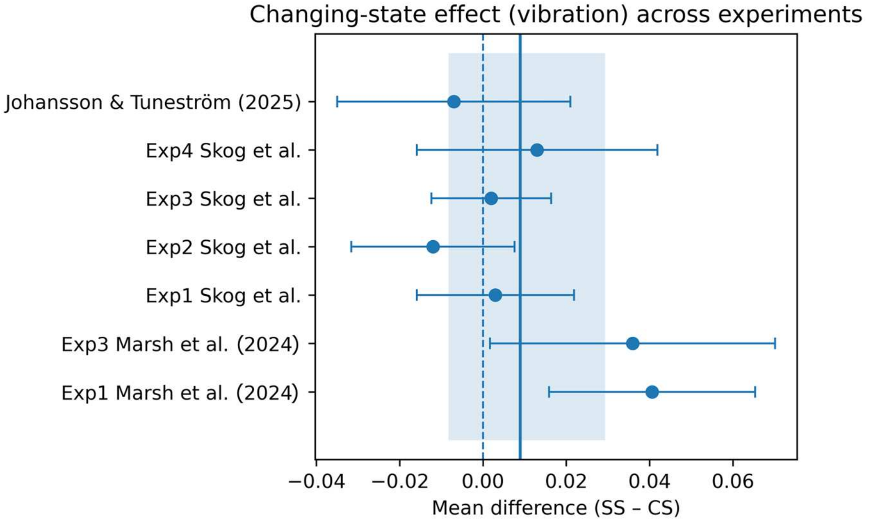

Figure 9. Forest plot of the vibrotactile changing-state effect (steady-state – changing-state) across seven experiments. Each point shows the standardised paired effect size (Cohen's d_z) for a single experiment, with horizontal lines indicating 95% confidence intervals based on the observed standard error of the difference scores. Positive values indicate poorer serial recall performance in the changing-state than in the steady-state condition. The vertical solid line marks the posterior mean of the pooled effect from the Bayesian random-effects meta-analysis ($d_z = 0.09$), and the shaded band represents its 95% highest-density interval.

Moreover, a meta-analysis synthesis provided moderate support for the null hypothesis ($BF_{01} = 6.79$), reinforcing the conclusion that vibrotactile changing-state sequences do not reliably impair serial recall. These findings challenge the generalizability of the changing-state effect to the tactile modality and raise important questions about the boundary conditions of serial recall interference.

Failure to replicate

Experiment 1 ($N = 40$) used a visual-verbal serial recall task and compared performance across steady- and changing-state sequences of vibrotactile stimuli. The results showed moderate evidence against the existence of a changing-state effect, $BF_{01} = 5.587$. Here, we report Bayes factors as BF_{01} to reflect that null effects dominated the outcomes. Experiment 2 ($N = 40$) replaced the verbal task with a visual-spatial serial recall task and again found moderate evidence against a vibrotactile changing-state effect, $BF_{01} = 3.0$. Experiment 3 ($N = 46$) expanded the design considerably, testing ten different vibrotactile sequences that varied in rhythm, intensity, spatial configuration, or their combinations. Yet again, there was moderate evidence against a vibrotactile changing-state effect, $BF_{01} = 6.024$. Finally, Experiment 4 ($N = 30$) completed the circle with an exact replication of the first experiment of Marsh, Vachon, et al. (2024), where there was again moderate evidence against a vibrotactile changing-state effect, $BF_{01} = 3.599$. Although Experiment 4 did not reproduce the auditory changing-state effect, both steady and changing-state auditory sequences produced clear disruption relative to quiet, confirming that the auditory manipulation was effective. Block order analyses also showed that this pattern was not attributable to sequence or learning effects. Occasional flattening of the changing-state increment is documented in the auditory literature, particularly in blocked designs, and does not conflict with the broader robustness of the auditory changing-state effect. For present purposes, the auditory result is not theoretically diagnostic; what matters is that vibrotactile variation failed to produce any interference across four experiments.

These results contrast sharply with those reported by Marsh, Vachon, et al. (2024). Their first experiment ($N = 30$) produced a medium effect size ($d_z = 0.588$) and strong Bayesian support for the vibrotactile changing-state hypothesis, $BF_{10} = 29.18$. Their third experiment (a probed order task) used a larger sample ($N = 72$) but yielded a smaller effect size ($d_z = 0.242$) and only anecdotal Bayesian support ($BF_{10} = 1.94$). In contrast, our new set of four experiments were powered to detect effects of the magnitude originally reported by Marsh, Vachon, et al. (2024) but consistently favoured the null hypothesis in both visual-verbal and visual-spatial serial recall tasks. It is therefore likely that Marsh, Vachon, et al.'s findings were false positives arising from sampling error, particularly given the relatively small sample in their first experiment. The present study illustrates the importance of replication, or at least using larger sample sizes, before new findings are used to draw strong theoretical conclusions, in general, and specifically about modality generality or amodal serial interference.

A limitation of the present study is that we have not exhaustively tested all possible forms of tactile serial interference. Three of our experiments focused on the form of distraction used in the initial report by Marsh, Vachon, et al. (2024), which was a spatially alternating sequence of vibrations across the hands. While Experiment 3 went further, testing more varied tactile stimulation, we never tested all these forms with the visual-spatial task, and we never replicated some of the (null) outcomes of Experiment 3. Thus, the forms of tactile stimulation tested in the present study qualify our conclusion that we find no evidence for a vibrotactile changing-state effect. Sample size can be considered a second limitation in the present study as our experiments were powered to detect effects of the magnitude originally reported by Marsh, Vachon, et al. (2024), which now appears to be a misleading estimate of the effect. We continue with a discussion on the theoretical implications of our result, and the possible requirements for vibrations to cause distraction.

Theoretical implications

The results from all four experiments suggest that a changing-state distraction effect does not emerge from irrelevant vibrotactile sequences when the to-be-remembered material is non-tactile. This conclusion is consistent with models that propose modality-specific mnemonic systems, such as the Working Memory Model (Baddeley, 1986, 2000, 2012), in which irrelevant vibrations would not gain access to a phonological store or visuo-spatial sketchpad unless they are recorded into a compatible representational format – something unlikely when the memoranda themselves are non-tactile.

Earlier support for the vibrotactile changing-state hypothesis was grounded in findings that tactile input can interfere with memory (Bancroft & Servos, 2011; see also Bancroft et al., 2013) and that vibrations can engage motor processes (Burton et al., 2004; Caetano & Jousmäki, 2006). Serial recall is often supported by motor-based rehearsal – speech motor processes in the case of verbal tasks (Hughes et al., 2009; Jones & Macken, 2018; Maidment & Macken, 2012; Schomers & Pulvermüller, 2016), and possibly eye movement patterns in the case of spatial tasks (Morey et al., 2018; Tremblay et al., 2006), but see Souza et al. (2020). From this perspective, irrelevant vibrations might be expected to interfere with either system. However, our results show no such interference in either modality. This may indicate that passive vibrotactile input fails to sufficiently engage the motoric processes involved in these tasks. Alternatively, it may indicate that such input is processed in a separate, modular working memory system, as proposed by Bancroft and Servos (2011). Additionally, tactile perception can produce streaming (Gallace & Spence, 2011), a perceptual organisation mechanism thought to underpin changing-state effects in other modalities. Yet, even with potential for tactile streaming, our findings showed no reliable distraction – suggesting that either streaming was not perceptually achieved or was insufficient to drive interference.

Clarifying this point is important: interference-by-process does not predict that any varying distractor stream should disrupt serial recall. Rather, it predicts disruption only when a distractor recruits the same ordering mechanisms that support serial rehearsal, typically speech–motor planning in verbal tasks (Hughes & Marsh, 2017; Jones & Macken, 2018; Linklater et al., 2024). Eye-movement routines and attentional refreshing do not meet this criterion (Souza et al., 2020), and the present findings suggest that vibrotactile sequences do not either. Their variation therefore fails to interact with, or intrude upon, the motoric sequencing processes that support serial recall. This explains the consistent null effects across our experiments without requiring rejection of interference-by-process accounts in the auditory domain.

The failure to replicate the vibrotactile changing-state effect casts doubt on the claim that such effects are amodal. Marsh, Vachon, et al. (2024) had interpreted their findings as evidence for an amodal workspace in which interference arises when two serial processes come into conflict. Our results suggest instead that such conflict may require representational compatibility, consistent with broader content-sensitive perspectives in memory research (e.g. Cowan, 1999; Neath, 2000; Oberauer et al., 2004; Page & Norris, 2003; Salamé & Baddeley, 1982), although these frameworks do not provide viable explanations of the changing-state effect itself. This conclusion is reinforced by recent work showing that auditory changing-state sequences, while reliably disruptive to verbal serial recall, do not impair performance in visual-spatial serial recall tasks (Marsh, Hurlstone, et al., 2024). This pattern parallels the present findings in the vibrotactile domain, where variation failed to disrupt either verbal or spatial short-term memory. Taken together, these findings suggest that changing-state interference may require more than just the presence of irrelevant serial order information, it may also depend on representational overlap or the involvement of shared ordering mechanisms. Our results do not rule out the existence of a common serial ordering system, but they imply that its susceptibility to disruption may be constrained by modality or representational format.

At minimum, our findings imply that vibrotactile distractors do not readily gain access to general-purpose serial ordering mechanism that operates across modalities.

However, vibrotactile changing-state distractors may simply fail to engage perceptual-motor coordination processes thought to underpin serial ordering in short-term memory (e.g. Hughes et al., 2009) or enter a shared representational space within which order is represented (Jones & Macken, 1993). While speculative, this could explain why the changing-state irrelevant vibrotactile stimuli did not produce interference-by-process. Thus, the null effect of the vibrotactile changing-state hypothesis does not necessarily undermine previous work on auditory distraction that have favoured the interference-by-process view (e.g. Hughes, 2014; Hughes & Marsh, 2017; Jones & Macken, 1993; Marsh et al., 2009) but instead point at the limits of the mechanisms' generalizability.

When do vibrations (not) cause distraction?

It is important to consider our findings from both interference-by-process and attentional-capture perspectives, because both frameworks offer accounts of the changing-state effect. Previous research has demonstrated that irrelevant vibrotactile stimuli can disrupt task performance, particularly when they are deviant or unexpected (Ljungberg & Parmentier, 2012; Marsja et al., 2018, 2019; Parmentier et al., 2011). Such effects are typically interpreted through the lens of attentional capture, where a salient change in the environment triggers an involuntary orienting response that briefly diverts attention from the focal task. According to the duplex-mechanism account (Hughes, 2014), this form of distraction is theoretically distinct from interference-by-process, as it does not rely on structural overlap between the distractor and focal task but rather on perceptual salience and surprise.

From this perspective, one might expect that *changing-state vibrotactile sequences*, which contain frequent perceptual changes, would also elicit attentional capture. Indeed, under the graded attentional model (e.g. Bell et al., 2019b) and Cowan's (1995) embedded-process model, the changing-state effect itself is viewed as a sequence of mini-deviants: each item-to-item change within the stream is thought to trigger a fresh orienting response. In this way, deviance effects (single unexpected events) and changing-state effects (repeated variation) are united under a common mechanism: disruption via involuntary attentional reorienting in response to perceptual change.

However, our findings pose a challenge to this attentional interpretation. Despite substantial variation in spatial location, intensity, and timing, none of the vibrotactile changing-state sequences disrupted performance in verbal serial recall. There was also no disruption to visual-spatial serial recall when vibrations alternated in spatial location. This absence of interference suggests that not all perceptual variation automatically elicits attentional capture, at least not to a degree sufficient to impair task performance.

One possible explanation is that the vibrotactile sequences, although variable, did not give rise to a coherent perceptual stream within which those changes could be detected as such. Prior work in the auditory domain has shown that changing-state effects depend critically on perceptual integration: when alternating stimuli are not grouped into a single stream, their changes are not perceived as variation within a coherent sequence and disruption is reduced (Jones & Macken, 1995; Kattner et al., 2024). If the vibrotactile sequences in our study were instead experienced as multiple steady sources (e.g. separate inputs to each hand), this could undermine the repeated orienting mechanism posited by attentional accounts.

Alternatively, it may be that attentional systems are less sensitive to change in the tactile modality than in the auditory modality. While isolated vibrotactile deviants have been shown to elicit distraction (e.g. Parmentier et al., 2011), our results suggest that ongoing variation, even rich and dynamic, does not necessarily accumulate as a series of attentional capture events in the same way that auditory variation does. In either case, our findings impose important constraints on attentional capture theories and their generality across sensory modalities. They suggest that perceptual change alone is not sufficient to cause distraction; disruption may also depend on whether the changes form an integrated perceptual stream that either triggers attentional orienting or engages serial processing mechanisms that overlap with those used in the focal task. Exploring this further is a target for future studies. Under the assumption that vibrotactile stimulation evokes motor responses (Burton et al., 2004; Caetano & Jousmäki, 2006), and the changing-state effect is underpinned by impaired motor-planning processes (Hughes, 2024), a vibrotactile changing-state effect may be revealed in conditions where short-term memory retention depends on those specific motor actions.

A further consideration relates to the role of environmental context in distraction. Recent work shows that the impact of irrelevant stimuli can depend on whether they are perceived as ambient background features of the environment or as task-bound events that are tightly coupled to the primary activity (Parmentier et al., 2022). From this perspective, the vibrotactile stimuli used in the present experiments were unlikely to function as contextual input: participants held the devices directly, and the vibrations formed an intrinsic part of the task apparatus rather than a diffuse environmental backdrop. Context-modulation accounts therefore predict comparatively weak distraction from such tightly coupled stimulation, consistent with the null results observed here. While speculative, this distinction further illustrates how the contextual status of vibrotactile input may constrain its ability to trigger either attentional diversion or interference-by-process.

Positioning the vibrotactile parameters within the tactile literature

During the review process a referee raised an important question concerning how the vibrotactile stimulation parameters used in the present experiments relate to established practices in tactile perception and memory research. We therefore briefly situate our manipulation within the broader vibrotactile literature. The stimulation frequency used in the present study (33 Hz) falls well within the range commonly employed in vibrotactile psychophysics. Frequencies between approximately 20 and 50 Hz predominantly engage rapidly adapting mechanoreceptive pathways and are widely used in studies examining tactile temporal pattern processing and suprathreshold discrimination (Gescheider et al., 2004; Hollins & Bensmaïa, 2007). Although higher frequencies can recruit additional mechanoreceptor channels, stimulation within this lower range is reliably perceived and routinely used in haptic cognition research. The amplitude of stimulation (2.3 m/s^2 RMS) likewise corresponds to a clearly suprathreshold yet moderate level of vibrotactile input. Detection thresholds for hand-held vibration vary substantially across individuals and anatomical locations, but typically lie well below this level (Gescheider et al., 2004; Verrillo, 1985). The present parameters were therefore selected to ensure consistent perceptibility while avoiding discomfort and excessive sensory adaptation. Individual variability in tactile sensitivity may nonetheless arise from factors such as hand size, grip configuration, and skin contact area. Larger contact areas can influence tactile perception because the area of skin contact and the distribution of mechanoreceptors determine how vibration energy is transmitted across the hand (Peters et al., 2009). Larger contact areas may reduce perceived intensity or spatial resolution, potentially introducing variability in how vibrotactile stimuli are experienced (Bhattacharjee et al., 2010; Dillon et al., 2001; Peters et al., 2009). Neither the present study nor Marsh, Vachon, et al. (2024) controlled for such factors, reflecting common practice in cognitive paradigms using hand-held vibrotactile stimulators. This limitation should therefore be interpreted as a general characteristic of the methodology rather than a unique feature of the current experiments.

Another relevant property of vibrotactile perception is sensory adaptation. Repeated vibration leads to reductions in perceived intensity and salience over time (Gescheider et al., 2004; Hollins et al., 1990). Such adaptation may attenuate the perceptual impact of repetitive distractor sequences. However, this characteristic reflects a fundamental modality-specific constraint and does not appear to differ between the present experiments and prior studies employing similar stimulation parameters. With respect to perceptual organisation, alternating stimulation across the hands was intended to create a varying distractor sequence analogous to auditory changing-state streams. However, tactile perceptual grouping differs from auditory streaming in important ways. Evidence suggests that stimulation delivered to spatially distinct body locations is often perceived as separate sources rather than as a single integrated dynamic stream (Gallace & Spence, 2011; Lin & Kashino, 2012). Consequently, spatial alternation alone may be insufficient to generate the coherent serial perceptual structure required for changing-state interference.

Finally, although some vibrotactile studies calibrate stimulus intensity individually relative to detection thresholds, such calibration is uncommon in cognitive distraction paradigms and was not implemented in either the present experiments or Marsh, Vachon, et al. (2024). Importantly, subjective reports from participants indicated that the vibrations were clearly perceptible throughout the tasks. In sum, these considerations suggest that the vibrotactile parameters employed here fall within the range typically used in tactile perception and working-memory research. Although individual variability and adaptation effects may modulate perceived salience, there is no clear indication that the present null results can be attributed to atypical or insufficient stimulation parameters. Rather, they are more plausibly interpreted as reflecting modality-specific limits on the capacity of vibrotactile variation to engage the serial-ordering processes implicated in changing-state interference.

Conclusions

The studied forms of changing-state vibrotactile stimuli do not interfere with serial recall in visual-verbal or visual-spatial tasks. Across four experiments, we failed to replicate the findings of Marsh, Vachon, et al. (2024), and Bayesian analyses consistently favoured the null hypothesis. These results suggest that vibrotactile variation may not be sufficient to enter or disrupt mnemonic processes that support serial ordering in non-tactile modalities. The results do not undermine the interference-by-process account of auditory distraction (e.g. Jones & Tremblay, 2000) but do call into question the claim that such effects are amodal. We suggest that vibrotactile distractors either do not engage the necessary perceptual-motor processes, or that their variation is not organised in a way that promotes interference with serial rehearsal mechanisms. In either case, the vibrotactile changing-state effect does not appear to exist, and our findings serve to update the academic record accordingly.

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Disclosure statement

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CRediT statement

Emil Skog: Conceptualisation, Investigation, Methodology, Software, Validation, Formal analysis, Data curation, Visualisation, Writing – original draft, Writing – review & editing. **John E. Marsh**: Conceptualisation, Methodology, Validation, Formal analysis, Writing – review & editing. **Jessica K. Ljungberg:** Conceptualisation, Resources, Writing – review & editing. **Patrik Sörqvist**: Conceptualisation, Methodology, Validation, Supervision, Writing – review & editing, Funding acquisition, Project administration.

References

Anderson, J. R. (1983). A spreading activation theory of memory. *Journal of Verbal Learning and Verbal Behavior*, *22*(3), 261–295. https://doi.org/10.1016/S0022-5371(83)90201-3

Baddeley, A. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences*, *4*(11), 417–423. https://doi.org/10.1016/S1364-6613(00)01538-2

Baddeley, A. (2012). Working memory: Theories, models, and controversies. *Annual Review of Psychology*, *63*(1), 1–29. https://doi.org/10.1146/annurev-psych-120710-100422

Baddeley, A. D. (1986). *Working memory*. Oxford University Press.

Baddeley, A. D., & Hitch, G. J. (1974). Working memory. In G. A. Bower (Ed.), *Recent advances in learning and motivation* (Vol. 8, pp. 47–89). Academic Press. https://doi.org/10.1016/s0079-7421(08)60452-1

Bancroft, T., & Servos, P. (2011). Distractor frequency influences performance in vibrotactile working memory. *Experimental Brain Research*, *208*(4), 529–532. https://doi.org/10.1007/s00221-010-2501-2

Bancroft, T. D., Hockley, W. E., & Servos, P. (2013). Irrelevant sensory stimuli interfere with working memory storage: Evidence from a computational model of prefrontal neurons. *Cognitive, Affective, & Behavioral Neuroscience*, *13*(1), 23–34. https://doi.org/10.3758/s13415-012-0131-9

Barrouillet, P., & Camos, V. (2012). As time goes by: Temporal constraints in working memory. *Current Directions in Psychological Science*, *21*(6), 413–419. https://doi.org/10.1177/0963721412459513

Bell, R., Röer, J. P., Lang, A.-G., & Buchner, A. (2019a). Reassessing the token set size effect on serial recall: Implications for theories of auditory distraction. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *45*(8), 1432–1440. https://doi.org/10.1037/xlm0000658

Bell, R., Röer, J. P., Lang, A.-G., & Buchner, A. (2019b). Distraction by steady-state sounds: Evidence for a graded attentional model of auditory distraction. *Journal of Experimental Psychology: Human Perception and Performance*, *45*(4), 500–512. https://doi.org/10.1037/xhp0000623

Bhattacharjee, A., Amanda, J. Y., Lisak, J. A., Vargas, M. G., & Goldreich, D. (2010). Vibrotactile masking experiments reveal accelerated somatosensory processing in congenitally blind braille readers. *The Journal of Neuroscience*, *30*(43), 14288–14298. https://doi.org/10.1523/JNEUROSCI.1447-10.2010

Bregman, A. S. (1990). *Auditory scene analysis: The perceptual organization of sound*. MIT Press.

Burton, H., Sinclair, R. J., & McLaren, D. G. (2004). Cortical activity to vibrotactile stimulation: An fMRI study in blind and sighted individuals. *Human Brain Mapping*, *23*(4), 210–228. https://doi.org/10.1002/hbm.20064

Caetano, G., & Jousmäki, V. (2006). Evidence of vibrotactile input to human auditory cortex. *Neuroimage*, *29*(1), 15–28. https://doi.org/10.1016/j.neuroimage.2005.07.023

Cowan, N. (1995). *Attention and memory: An integrated framework*. Oxford University Press.

Cowan, N. (1999). Models of working memory. *Models of Working Memory: Mechanisms of Active Maintenance and Executive Control*, *20*(506), 62–101. https://doi.org/10.1017/CBO9781139174909.006

Craig, J. C. (1980). Modes of vibrotactile pattern generation. *Journal of Experimental Psychology: Human Perception and Performance*, *6*(1), 151–166. https://doi.org/10.1037/0096-1523.6.1.151

De Lillo, C., Kirby, M., & Poole, D. (2016). Spatio-temporal structure, path characteristics, and perceptual grouping in immediate serial spatial recall. *Frontiers in Psychology*, *7*, Article 1686. https://doi.org/10.3389/fpsyg.2016.01686

Dillon, Y. K., Haynes, J., & Henneberg, M. (2001). The relationship of the number of Meissner's corpuscles to dermatoglyphic characters and finger size. *Journal of Anatomy*, *199*(5), 577–584. https://doi.org/10.1046/j.1469-7580.2001.19950577.x

Farrell, S., & Lewandowsky, S. (2002). An endogenous distributed model of ordering in serial recall. *Psychonomic Bulletin & Review*, *9*(*1*), 59–79. https://doi.org/10.3758/BF03196257

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191. https://doi.org/10.3758/BF03193146

Gallace, A., & Spence, C. (2011). To what extent do Gestalt grouping principles influence tactile perception? *Psychological Bulletin*, *137*(4), 538–561. https://doi.org/10.1037/a0022335

Gescheider, G. A., Bolanowski, S. J., & Verrillo, R. T. (2004). Some characteristics of tactile channels. *Behavioural Brain Research*, *148*(1-2), 35–40. https://doi.org/10.1016/S0166-4328(03)00177-3

Guerard, K., & Tremblay, S. (2012). The effect of path length and display size on memory for spatial information. *Experimental Psychology*, *59*(3), 147–152. https://doi.org/10.1027/1618-3169/a000137

Hanley, J. R., & Bakopoulou, E. (2003). Irrelevant speech, articulatory suppression, and phonological similarity: A test of the phonological loop model and the feature model. *Psychonomic Bulletin & Review*, *10*(2), 435–444. https://doi.org/10.3758/BF03196503

Henson, R., Hartley, T., Burgess, N., Hitch, G., & Flude, B. (2003). Selective interference with verbal short-term memory for serial order information: A new paradigm and tests of a timing-signal hypothesis. *The Quarterly Journal of Experimental Psychology Section A*, *56*(8), 1307–1334. https://doi.org/10.1080/02724980244000747

Hollins, M., & Bensmaïa, S. J. (2007). The coding of roughness. *Canadian Journal of Experimental Psychology / Revue canadienne de psychologie expérimentale*, *61*(3), 184–195. https://doi.org/10.1037/cjep2007020

Hollins, M., Goble, A. K., Whitsel, B. L., & Tommerdahl, M. (1990). Time course and action spectrum of vibrotactile adaptation. *Somatosensory & Motor Research*, *7*(2), 205–221. https://doi.org/10.3109/08990229009144707

Hughes, R. W. (2014). Auditory distraction: A duplex-mechanism account. *PsyCh Journal*, *3*(1), 30–41. https://doi.org/10.1002/pchj.44

Hughes, R. W. (2024). The phonological store of working memory: A critique and an alternative, perceptual-motor, approach to verbal short-term memory. *Quarterly Journal of Experimental Psychology*, *78*(2), 240–263. https://doi.org/10.1177/17470218241257885

Hughes, R. W., & Marsh, J. E. (2017). The functional determinants of short-term memory: Evidence from perceptual-motor interference in verbal serial recall. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *43*(4), 537–551. https://doi.org/10.1037/xlm0000325

Hughes, R. W., Marsh, J. E., & Jones, D. M. (2009). Perceptual-gestural (mis)mapping in serial short-term memory: The impact of talker variability. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *35(6)*, 1411–1425. https://doi.org/10.1037/a0017008

Hughes, R. W., Vachon, F., & Jones, D. M. (2005). Auditory attentional capture during serial recall: Violations at encoding of an algorithm-based neural model? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *31*(4), 736–749. https://doi.org/10.1037/0278-7393.31.4.736

Hughes, R. W., Vachon, F., & Jones, D. M. (2007). Disruption of short-term memory by changing and deviant sounds: Support for a duplex-mechanism account of auditory distraction. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *33*(6), 1050–1061. https://doi.org/10.1037/0278-7393.33.6.1050

Johansson, H., & Tuneström, F. (2025). *Kan changing-state stjälpa och steady-state hjälpa? Sekvensberoende effekter av vibrotaktila devianter vid seriell återgivning* [Unpublished bachelor's thesis]. Luleå University of Technology. https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1968970&dswid=2225

Johnson, A. J., Skinner, R., Takwoingi, P., & Miles, C. (2019). Tactile memory ranschburg effects under conditions of concurrent articulation. *Quarterly Journal of Experimental Psychology*, *72*(7), 1855–1862. https://doi.org/10.1177/1747021819844758

Jones, D., Farrand, P., Stuart, G., & Morris, N. (1995). Functional equivalence of verbal and spatial information in serial short-term memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *21*(*4*), 1008–1018. https://doi.org/10.1037/0278-7393.21.4.1008

Jones, D., Madden, C., & Miles, C. (1992). Privileged access by irrelevant speech to short-term memory: The role of changing state. *The Quarterly Journal of Experimental Psychology Section A*, *44*(4), 645–669. https://doi.org/10.1080/14640749208401304

Jones, D. M., & Macken, B. (2018). In the beginning was the deed: Verbal short-term memory as object-oriented action. *Current Directions in Psychological Science*, *27*(5), 351–356. https://doi.org/10.1177/0963721418765796

Jones, D. M., & Macken, W. J. (1993). Irrelevant tones produce an irrelevant speech effect: Implications for phonological coding in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *19*(2), 369–381. https://doi.org/10.1037/0278-7393.19.2.369

Jones, D. M., & Macken, W. J. (1995). Organizational factors in the effect of irrelevant speech: The role of spatial location and timing. *Memory & Cognition*, *23*(2), 192–200. https://doi.org/10.3758/BF03197221

Jones, D. M., & Tremblay, S. (2000). Interference in memory by process or content? A reply to Neath (2000). *Psychonomic Bulletin & Review*, *7*(3), 550–558. https://doi.org/10.3758/BF03214370

Kattner, F., Hassanzadeh, M., & Ellermeier, W. (2024). The role of spatial location in irrelevant speech revisited: A preregistered replication study. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *50*(12), 1892–1900. https://doi.org/10.1037/xlm0001424

LeCompte, D. C., Neely, C. B., & Wilson, J. R. (1997). Irrelevant speech and irrelevant tones: The relative importance of speech to the irrelevant speech effect. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *23*(2), 472–483. https://doi.org/10.1037/0278-7393.23.2.472

Lin, I. F., & Kashino, M. (2012). Perceptual grouping over time within and across auditory and tactile modalities. *PLoS*

One, *7*(7), e41661. https://doi.org/10.1371/journal.pone.0041661

Linklater, R. D., Judge, J., Sörqvist, P., & Marsh, J. E. (2024). Auditory distraction of vocal-motor behaviour by different components of song: Testing an interference-by-process account. *Journal of Cognitive Psychology*, *36*(1), 101–137. https://doi.org/10.1080/20445911.2023.2284404

Ljungberg, J. K., & Parmentier, F. B. (2012). Cross-modal distraction by deviance: Functional similarities between the auditory and tactile modalities. *Experimental Psychology*, *59*(6), 355–363. https://doi.org/10.1027/1618-3169/a000164

MacDermid, A. E., Duggan, V. A., Miller, B. L., Neath, I., & Surprenant, A. M. (2023). Irrelevant speech, changing state, and order information. *Memory & Cognition*, *51*(8), 1836–1848. https://doi.org/10.3758/s13421-023-01437-z

Maidment, D. W., & Macken, W. J. (2012). The ineluctable modality of the audible: Perceptual determinants of auditory verbal short-term memory. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(4), 989–997. https://doi.org/10.1037/a0027884

Marsh, J. E., Hughes, R. W., & Jones, D. M. (2009). Interference by process, not content, determines semantic auditory distraction. *Cognition*, *110*(1), 23–38. https://doi.org/10.1016/j.cognition.2008.08.003

Marsh, J. E., Hurlstone, M. J., Marois, A., Ball, L. J., Moore, S. B., Vachon, F., Schlittmeier, S. J., Röer, J. P., Buchner, A., Aust, F., & Bell, R. (2024). Changing-state irrelevant speech disrupts visual–verbal but not visual–spatial serial recall. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *50*(11), 1772–1790. https://doi.org/10.1037/xlm0001360

Marsh, J. E., Vachon, F., Sörqvist, P., Marsja, E., Röer, J. P., Richardson, B. H., & Ljungberg, J. K. (2024). Irrelevant changing-state vibrotactile stimuli disrupt verbal serial recall: Implications for theories of interference in short-term memory. *Journal of Cognitive Psychology*, *36*(1), 78–100. https://doi.org/10.1080/20445911.2023.2198065

Marsja, E., Marsh, J. E., Hansson, P., & Neely, G. (2019). Examining the role of spatial changes in bimodal and unimodal to-be-ignored stimuli and how they affect short-term memory processes. *Frontiers in Psychology*, *10*, Article 299. https://doi.org/10.3389/fpsyg.2019.00299

Marsja, E., Neely, G., & Ljungberg, J. K. (2018). Investigating deviance distraction and the impact of the modality of the to-be-ignored stimuli. *Experimental Psychology*, *65*(2), 61–70. https://doi.org/10.1027/1618-3169/a000390

McGeoch, J. A. (1942). *The psychology of human learning: An introduction*. Longmans.

Mensink, G. J., & Raaijmakers, J. G. (1988). A model for interference and forgetting. *Psychological Review*, *95*(4), 434–455. https://doi.org/10.1037/0033-295X.95.4.434

Morey, C. C., Mareva, S., Lelonkieqicz, J. R., & Chevalier, N. (2018). Gaze-based rehearsal in children under 7: A developmental investigation of eye movements during a serial spatial memory task. *Developmental Science*, *21*(3), e12559. https://doi.org/10.1111/desc.12559

Neath, I. (2000). Modeling the effects of irrelevant speech on memory. *Psychonomic Bulletin & Review*, *7*(3), 403–423. https://doi.org/10.3758/bf03214356

Oberauer, K. (2009). Interference between storage and processing in working memory: Feature overwriting, not similarity-based competition. *Memory & Cognition*, *37*(3), 346–357. https://doi.org/10.3758/MC.37.3.346

Oberauer, K., & Kliegl, R. (2006). A formal model of capacity limits in working memory. *Journal of Memory and Language*, *55*(4), 601–626. https://doi.org/10.1016/j.jml.2006.08.009

Oberauer, K., & Lange, E. B. (2008). Interference in verbal working memory: Distinguishing similarity-based confusion, feature overwriting, and feature migration. *Journal of Memory and Language*, *58*(3), 730–745. https://doi.org/10.1016/j.jml.2007.09.006

Oberauer, K., Lange, E. B., & Engle, R. W. (2004). Working memory capacity and resistance to interference. *Journal of Memory and Language*, *51*(1), 80–96. https://doi.org/10.1016/j.jml.2004.03.003

Oberauer, K., Lewandowsky, S., Awh, E., Brown, G. D. A., Conway, A., Cowan, N., Donkin, C., Farrell, S., Hitch, G. J., Hurlstone, M. J., Ma, W. J., Morey, C. C., Nee, D. E., Schweppe, J., Vergauwe, E., & Ward, G. (2018). Benchmarks for models of short-term and working memory. *Psychological Bulletin*, *144*(9), 885–958. https://doi.org/10.1037/bul0000153

Page, M. P., & Norris, D. G. (2003). The irrelevant sound effect: What needs modelling, and a tentative model. *The Quarterly Journal of Experimental Psychology Section A*, *56*(8), 1289–1300. https://doi.org/10.1080/02724980343000233

Parmentier, F. B. (2008). Towards a cognitive model of distraction by auditory novelty: The role of involuntary attention capture and semantic processing. *Cognition*, *109*(3), 345–362. https://doi.org/10.1016/j.cognition.2008.09.005

Parmentier, F. B., & Andrés, P. (2006). The impact of path crossing on visuo-spatial serial memory: Encoding or rehearsal effect? *Quarterly Journal of Experimental Psychology*, *59*(11), 1867–1874. https://doi.org/10.1080/17470210600872154

Parmentier, F. B., Andrés, P., Elford, G., & Jones, D. M. (2006). Organization of visuo-spatial serial memory: Interaction of temporal order with spatial and temporal grouping. *Psychological Research Psychologische Forschung*, *70*(3), 200–217. https://doi.org/10.1007/s00426-004-0212-7

Parmentier, F. B., Elford, G., & Maybery, M. (2005). Transitional information in spatial serial memory: Path characteristics affect recall performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *31*(3), 412–427. https://doi.org/10.1037/0278-7393.31.3.412

Parmentier, F. B., Ljungberg, J. K., Elsley, J. V., & Lindkvist, M. (2011). A behavioral study of distraction by vibrotactile novelty. *Journal of Experimental Psychology: Human Perception and Performance*, *37*(4), 1134–1139. https://doi.org/10.1037/a0021931

Parmentier, F. B. R., Gallego, L., Micucci, A., Leiva, A., Andrés, P., & Maybery, M. T. (2022). Distraction by deviant sounds is modulated by the environmental context. *Scientific Reports*, *12*(*1*), 527. https://doi.org/10.1038/s41598-022-25500-y

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., & Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods*, *51*(*1*), 195–203. https://doi.org/10.3758/s13428-018-01193-y

Peters, R. M., Hackeman, E., & Goldreich, D. (2009). Diminutive digits discern delicate details: Fingertip size and the sex difference in tactile spatial acuity. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *29*(50), 15756–15761. https://doi.org/10.1523/JNEUROSCI.3684-09.2009

Roe, D., Allen, R. J., Elsley, J., Miles, C., & Johnson, A. J. (2024). Working memory prioritisation effects in tactile immediate serial recall. *Quarterly Journal of Experimental Psychology*, *77*(11), 2354–2363. https://doi.org/10.1177/17470218241231283

Röer, J. P., Bell, R., & Buchner, A. (2014). Evidence for habituation of the irrelevant-sound effect on serial recall. *Memory & Cognition*, *42*(4), 609–621. https://doi.org/10.3758/s13421-013-0381-y

Salamé, P., & Baddeley, A. (1990). The effects of irrelevant speech on immediate free recall. *Bulletin of the Psychonomic Society*, *28*(6), 540–542. https://doi.org/10.3758/BF03334073

Salamé, P., & Baddeley, A. D. (1982). Disruption of short-term memory by unattended speech: Implications for the structure of working memory. *Journal of Verbal Learning and Verbal Behavior*, *21*(2), 150–164. https://doi.org/10.1016/S0022-5371(82)90521-7

Schomers, M. R., & Pulvermüller, F. (2016). Is the sensorimotor cortex relevant for speech perception and understanding? An integrative review. *Frontiers in Human Neuroscience*, *10*, Article 435. https://doi.org/10.3389/fnhum.2016.00435

Sörqvist, P. (2010). High working memory capacity attenuates the deviation effect but not the changing-state effect: Further support for the duplex-mechanism account of auditory distraction. *Memory & Cognition*, *38*(5), 651–658. https://doi.org/10.3758/MC.38.5.651

Souza, A. S., Czoschke, S., & Lange, E. B. (2020). Gaze-based and attention-based rehearsal in spatial working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *46*(5), 980–1003. https://doi.org/10.1037/xlm0000771

Tremblay, S., & Jones, D. M. (1998). Role of habituation in the irrelevant sound effect: Evidence from the effects of token set size and rate of transition. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *24*(3), 659–671. https://doi.org/10.1037//0278-7393.24.3.659

Tremblay, S., Saint-Aubin, J., & Jalbert, A. (2006). Rehearsal in serial memory for visual-spatial information: Evidence from eye movements. *Psychonomic Bulletin & Review*, *13*(3), 452–457. https://doi.org/10.3758/BF03193869

Vachon, F., Labonté, K., & Marsh, J. E. (2017). Attentional capture by deviant sounds: A noncontingent form of auditory distraction? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *43*(4), 622–634. https://doi.org/10.1037/xlm0000330

Vergauwe, E., Barrouillet, P., & Camos, V. (2010). Do mental processes share a domain-general resource? *Psychological Science*, *21*(3), 384–390. https://doi.org/10.1177/0956797610361340

Verrillo, R. T. (1985). Psychophysics of vibrotactile stimulation. *The Journal of the Acoustical Society of America*, *77*(1), 225–232. https://doi.org/10.1121/1.392263

Appendix A

Stimulus paths used in Experiment 2.

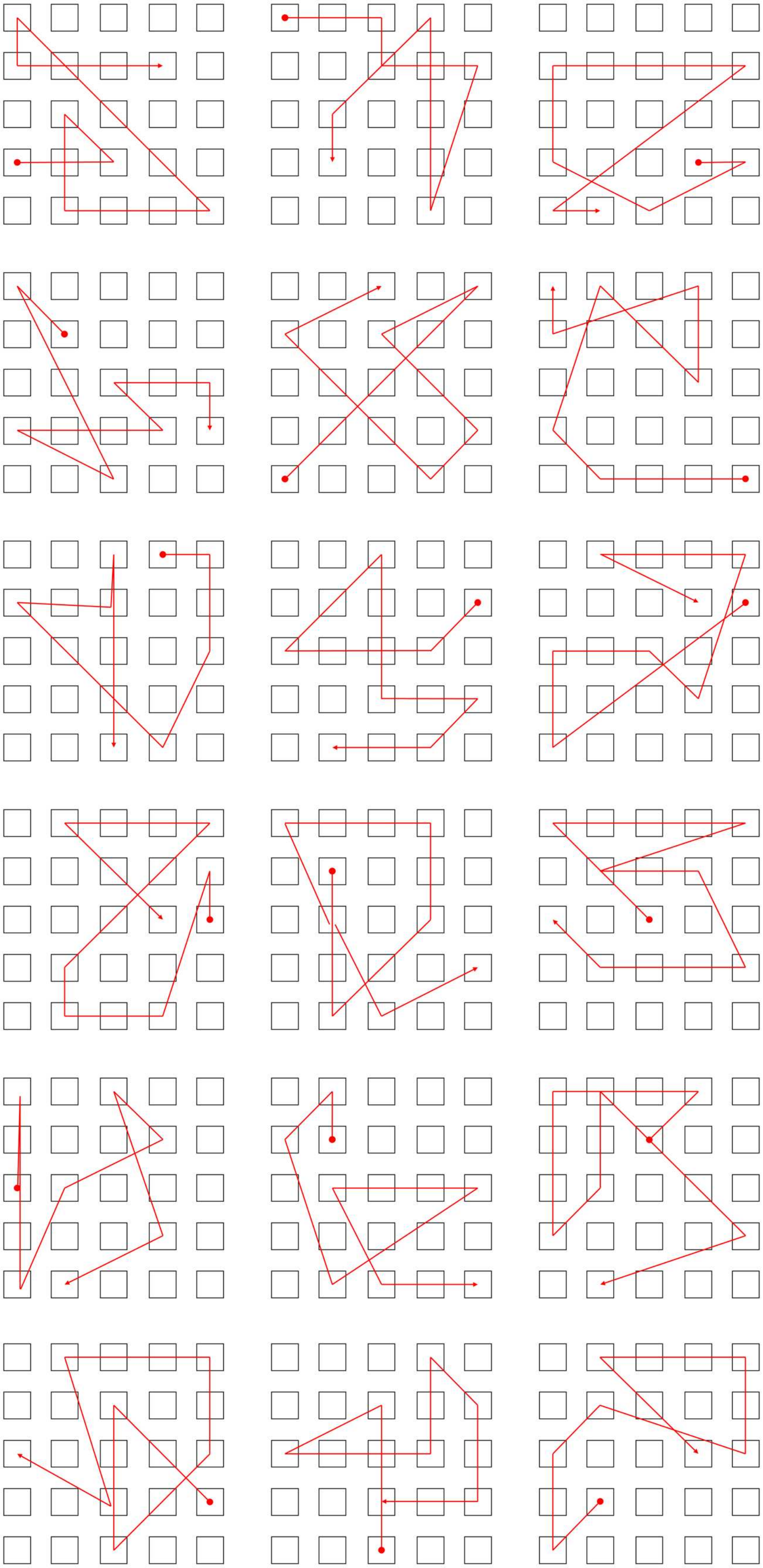

Figure A1. Representations of the eighteen stimulus paths used in Experiment 2. Mirrored versions occurred, see text for details.