Cross-modal serial dependence emerges in sequential numerosity comparison task

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Abstract

Serial dependence is a phenomenon in which current perception is attracted to the immediately preceding perception and is thought to reflect a mechanism for stabilizing perception. It has been demonstrated across a variety of stimuli and has also been observed in the numerosity perception. A previous study suggested that cross-modal serial dependence in numerosity perception from audition to vision did not occur; however, differences in the stimulus presentation format might have prevented serial dependence from emerging. Therefore, we used a standardized temporal presentation format. As a result, we observed bidirectional cross-modal serial dependence between audition and vision. However, the effects in each direction were not consistent within individuals. These findings provide important insights into the mechanisms underlying serial dependence, indicating that both higher-level processing, such as abstract numerical representation, and lower-level processing, such as auditory and visual cortex involvement, are engaged in cross-modal serial dependence in numerosity perception.

Keywords: serial dependence; numerosity perception; cross-modal; vision; audition

Introduction

Although sensory inputs are inherently unstable and contain substantial noise, our perception remains remarkably stable. This stability is thought to be achieved by utilizing the autocorrelative properties of the external environment. Such a strategy is observed as “serial dependence” in perception, defined as the phenomenon wherein the current perception is biased by the perception in the previous moments. More detailed discussions can be found in recent review articles (Cicchini et al., 2024; Manassi et al., 2023; Pascucci et al., 2023).

Serial dependence has been treated as an artifact that appears in behavioral experiments. However, in 2014, Fischer and colleagues conducted a detailed analysis of serial dependence in orientation perception and proposed a view that considers it as a crucial phenomenon reflecting a mechanism for stabilizing perception (Fischer & Whitney, 2014). Around the same time, Cicchini and colleagues demonstrated the presence of serial dependence in numerical perception (Cicchini et al., 2014). Motivated by these findings, subsequent research has reported serial dependence in various visual features, including face perception (Liberman et al., 2014; Taubert et al., 2016; Van der Burg et al., 2019), motion perception (Alais et al., 2017), and rating artworks (Kim et al., 2019). Serial dependence has also been demonstrated in other modalities, such as modulation frequency of an amplitude-modulated sound (Motala et al., 2020), pitch (Arzounian et al., 2017), duration of auditory stimuli (Li et al., 2023), emotion of spoken sentence (Van der Burg et al., 2024), vestibular-based distance perception (Willemsen et al., 2024), tactile orientation perception (Wang & Alais, 2024), and odor perception (Van der Burg et al., 2022). Taken together, these findings suggest that serial dependence emerges in a broad variety of stimuli, irrespective of the complexity of stimulus features or the sensory modality involved. Thus, serial dependence may represent a ubiquitous nature underlying how humans infer states of the external world.

One of the central debates regarding the mechanism of serial dependence concerns the processing stage at which it arises. Initially, serial dependence was considered to emerge in lower-level perceptual processing (Fischer & Whitney, 2014; John-Saaltink et al., 2016). However, it has become evident that higher-level processes are also involved, as attention (Fischer & Whitney, 2014; Fritsche & de Lange, 2019) and stimulus awareness (Fu & Mei, 2024; Kim et al., 2020) affect serial dependence. Further support for the involvement of higher-level processing comes from findings that serial dependence occurs with approximating monetary values (Morimoto & Makioka, 2022) and is influenced by visual illusions (Cicchini et al., 2021). On the other hand, the observation that serial dependence can occur without an explicit task (Fornaciai & Park, 2018a; Murai & Whitney, 2021) and that it directly modulates perception (Cicchini et al., 2017) still suggests a role of lower-level processes. These suggest that both higher-level and lower-level processing are implicated in the generating serial dependence (Ceylan et al., 2021; Pascucci et al., 2023; Cicchini et al., 2021).

One factor complicating the debate over the mechanisms of serial dependence is the inconsistency in observed properties of serial dependence across different stimulus features and tasks. This variability is thought to arise from differences in the processing involved and its properties, which vary depending on the stimulus and tasks. The present study therefore examines the processing stages of serial dependence in numerosity perception, a domain whose processing is relatively well characterized. Numerical perception is known to be structured as a consistent hierarchical process (Castaldi et al., 2019; Kido et al., 2025) from lower-level perceptual processing (DeWind et al., 2019;

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Fornaciai et al., 2017) to higher-level processing (Eger et al., 2009; Nieder et al., 2002; Sokolowski et al., 2017). However, it is important to note that there is ongoing debate over whether the representation at lower-level perceptual processing already integrates numerical information, or whether it instead encodes lower-level features—such as spatial frequency—which correlate with the number of stimuli (Castaldi et al., 2019; Park & Huber, 2022; Paul et al., 2022).

Whether serial dependence arises across sensory modalities is a key question for investigating at which processing stages serial dependence occurs. Sensory inputs from modality-specific receptors (e.g., visual, auditory) are initially processed in modality-specific areas, such as the visual and auditory cortices, and are gradually integrated as they are relayed to higher-level regions. Therefore, investigating whether serial dependence occurs across different modalities can provide valuable insights into the extent to which higher-level processing contributes to serial dependence. Fornaciai and Park examined serial dependence induced by temporally presented numerical stimuli—sequences of flashes or tones—in numerosity perception from spatially presented visual stimuli (dot arrays) (Fornaciai & Park, 2019). Their results indicated that sequences of flashes attracted the perceived numerosity of following dot arrays, whereas auditory stimuli did not. In other words, serial dependence in numerosity perception occurred across presentation formats (temporal and spatial) within a modality, but not across modalities. This finding suggests that serial dependence arises at a stage that is unaffected by lower features specific to each presentation format and does not generalize across sensory modalities. The absence of cross-modal serial dependence is also demonstrated in the classification of visual and auditory stimulus durations (Li et al., 2023).

In contrast, some studies have provided evidence for the presence of cross-modal serial dependence. For example, Burg and colleagues demonstrated audiovisual serial dependence in a task requiring emotional evaluations of presented images and sounds (Burg et al., 2021). One possible explanation is that the brain regions involved in emotional processing do not exhibit modality selectivity. Given the existence of abstract numerical representations that are generalized across modalities, it is possible that cross-modal effects could also emerge in numerosity perception.

In the experiment by Fornaciai and colleagues, which reported no cross-modal effect on numerosity perception, both modality and presentation format were varied (Fornaciai & Park, 2019). Specifically, while the inducer stimulus was an auditory stimulus that represented numerosity temporally, participants judged the numerical magnitude of dot arrays which represented numerosity spatially. Results using temporal visual stimuli as the inducer indicated that, within the visual modality, the occurrence of serial dependence was unaffected by the presentation format. However, it remains unclear whether the absence of cross-modal serial dependence was due to the difference in presentation format. Furthermore, the previous study has only investigated an auditory-to-visual effect. Therefore, in the present study, we standardized the presentation format to a temporal format and investigated whether serial dependence in numerosity perception occurs bidirectionally between the vision and audition. Should a cross-modal effect emerge, it would imply that a higher-level, modality-generalized abstract representation of numerosity is involved in serial dependence.

Method

Participants

Thirty-nine students (9 males, 30 females; M_{age} = 20.64, SD_{age} = 4.91) from Osaka Metropolitan University took part in the study. All participants provided written informed consent and received either course credit or a payment of 1,500 JPY. The sample size was determined a priori using G*Power 3.1 (Faul et al., 2007), based on an effect size (Cohen's *dz* = 0.6) assumed in Fornaciai and Park (2019). Under this assumption, the main analysis—a two-sided paired t-test—would achieve a power of 0.95 at an alpha level of 0.05. Although a one-sided test was employed in the previous study, a two-sided test was adopted here to account for the possibility of effects in the opposite direction. The experimental protocol was approved by the Research Ethics Committee of the Graduate School of Sustainable System Sciences at Osaka Metropolitan University.

Apparatus and Stimuli

The experiment was conducted on a Linux PC (OS: Ubuntu 20.04 LTS, CPU: Intel Core i7-8700, GPU: GeForce GTX 1080Ti 11GB GDDR5X) using MATLAB (version 2021a, The MathWorks Inc., Natick, MA, USA) in conjunction with Psychtoolbox-3 (Brainard, 1997; Pelli, 1997). Visual and Auditory stimuli representing numerosity temporally were employed: a sequence of white dot flashes displayed on a monitor, and a sequence of bursts of white noise reproduced through speakers. The timing of flashes and noises in sequences, as well as the waveform data of auditory stimuli, were pre-generated using MATLAB. Visual stimuli were presented on a 24-inch LCD monitor (ASUS VG248QE; 1920 × 1080 pixels), placed approximately 50 cm in front of participants. The monitor's refresh rate was set to 60 Hz. Auditory stimuli were presented through speakers (JBL PEBBLES) placed behind the monitor, which were spatially aligned with the left and right positions of the visual stimuli. Participant responses were collected using a USB keyboard.

The visual stimulus was a sequence of white dot flash (Figure 1). The dot had a radius of 10 pixels (visual angle: 0.3°) and was presented 200 pixels (6.3°) to the left or right of the center of the screen. The number of flashes ranged from 5 to 21. Each flash lasted for 50 ms, which corresponds to 3 frames at the monitor's refresh rate of 60 Hz. The total duration of the visual stimulus was 3,000 ms (1,80 frames). All stimuli contained a flash in the first and last 50 ms, and remaining flash onsets were randomly determined in each stimulus. To prevent both consecutive flashes and extreme skewness in the onset distribution, only sequences with inter-flash intervals of at least 50 ms and a skewness less than 0.8 were used.

The auditory stimuli were sequences of bursts of white noise (Figure 1) played from either the left or the right speaker at a sampling rate of 44,100 Hz. The number of white-noise bursts ranged from 5 to 21, with each burst lasting 24 ms (1,050 samples). The total duration of the auditory stimulus was 1,429 ms (63,000 samples). All stimuli contained a noise in the first and last 24 ms, and remaining noise onsets were randomly determined in each stimulus. As with the visual stimuli, only sequences with inter-noise intervals of at least 24 ms and an onset distribution skewness below 0.8 were employed. That is, the auditory stimulus corresponded to approximately 0.48 times the duration of the visual stimulus. This adjustment was made to ensure that both stimuli were challenging enough to discourage counting while still allowing participants to perform the numerical comparison task.

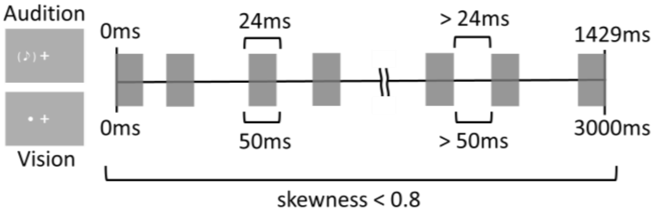

Figure 1: Schematic illustration of the visual and auditory stimuli. Each gray rectangle in the figure corresponds to either a flash or burst of white noise. The timing of flashes and white-noise bursts was randomly determined, and only sequences that met the predefined criteria were used.

Procedure

The main task was a numerosity comparison of stimulus elements (i.e., flashes or bursts of white noise) between the reference and probe stimuli (Figure 2). In each trial, either a visual or an auditory stimulus was presented in the order of Inducer, Reference, and Probe. In the visual induction condition, the inducer was a visual stimulus while the reference and probe were auditory stimuli. In the auditory-induction condition, the inducer was an auditory stimulus while the reference and probe were visual stimuli. The inducer consisted of either 7 or 19 elements, the probe contained an odd number of elements ranging from 5 to 21 (9 possible values), and the reference consistently contained 13 elements. The inducer and reference stimuli were presented on the same side of the screen or speaker, while the probe was presented on the opposite side. A white fixation cross (15 × 15 pixels) was displayed continuously at the center of the screen. Following the probe stimulus, a prompt was displayed, instructing participants to indicate which stimulus (reference or probe) had more elements. Therefore, participants always compared stimuli in the same modality. They were informed that the inducer was irrelevant to the comparison task.

To ensure participants' attention to the inducer, we implemented a catch trial in which participants categorized the inducer as "many" or "few." Examples of the inducer stimuli were provided during the instructions to clarify this categorization. These catch trials were unexpectedly interspersed throughout the main task to ensure sustained attention to the inducer.

After providing written informed consent, participants received an explanation of the structure of a single trial and the overall tasks. They then completed seven practice trials of the main task for each of the visual induction and auditory induction conditions, followed by instructions and a practice trial of the catch trial for each condition.

The main task comprised 216 trials in each condition. One condition was administered in the first half of the experiment and the other in the second half, with the order counterbalanced across participants. The presentation position of the stimulus (left or right) was randomized with equal occurrences across trials. During the main task, 15 catch trials per condition were administered at randomly determined intervals. The experiment lasted approximately 90 minutes, and participants were permitted to take breaks of unrestricted duration every 77 trials.

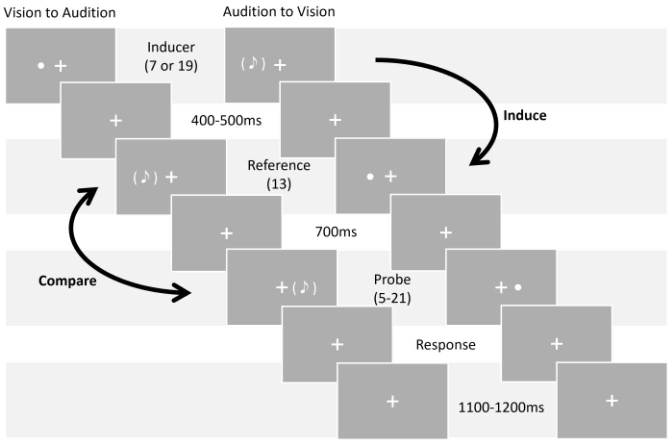

Figure 2: Procedure for a single trial. Both the visual induction and auditory induction conditions followed the same procedure. Following the presentation of the probe stimulus, participants were asked to judge whether the reference or the probe stimulus contained more elements. The visual stimuli lasted 3000 ms, while the auditory stimuli lasted 1429 ms. The inducer was initially presented, followed by the reference after an interval of 400-500 ms, and then the probe 700 ms later. The interval between trials was 1100–1200 ms.

Analysis

Analyses were conducted for each participant (n = 39) and condition (auditory induction and visual induction) using MATLAB and the Palamedes toolbox (Prins & Kingdom, 2018). The significance level was set at 0.05 for all analyses.

A cumulative Gaussian function was fitted to each participant's responses using the maximum-likelihood method to obtain a psychometric function. We defined the point of subjective equality (PSE) as the median of the psychometric function. The just noticeable difference (JND) was defined as the difference in the number of stimulus elements between the points at which participants responded "the probe stimulus contains more elements than the reference" at rates of 50% and 75%."

Before conducting any analyses, we excluded data from participants who were judged unable to perform the task properly. Specifically, participants were excluded if their JND exceeded 10 or if their PSE deviated by more than 3 SD from the mean of all participants. These criteria followed a previous study (Fornaciai & Park, 2019). If a participant met either exclusion criterion in any condition, their data were excluded from all conditions. As a result, four participants were excluded from the analyses.

Serial dependence was assessed by examining whether the PSE in the subsequent comparison task differed depending on whether the inducer stimulus contained 19 or 7 elements. A two-tailed paired t-test was conducted to examine whether the mean PSE values differed between the many-inducer and few-inducer conditions.

In addition, we evaluated the within-subject consistency of the serial dependence effect observed under the auditory and visual induction conditions. For each participant, the difference in PSE between the large-inducer and small-inducer conditions ($\text{PSE}_{\text{inducer19}}$ - $\text{PSE}_{\text{inducer7}}$) was calculated and used as an index of the serial dependence effect. Since both the auditory and visual induction conditions were within-subject factors, we were able to examine whether the serial dependence effect was consistent within individuals across the two conditions. To assess consistency, Spearman's rank correlation coefficient was calculated between the two conditions. Since the auditory induction condition involved comparisons between visual stimuli, whereas the visual induction condition involved comparisons between auditory stimuli, we did not assume linearity in serial dependence effects across the two conditions. Therefore, we adopted rank correlation, which does not require a linear relationship between variables. Kondo et al. (2022) similarly employed a rank correlation to examine the relationship of serial dependence across data collected on different days.

Results

To provide an overview of the results, Figure 3 presents the psychometric functions fitted to the aggregated data from all participants. In both the auditory induction and visual induction conditions, the point of subjective equality (PSE) was higher following an inducer with a larger number of elements compared to an inducer with fewer elements. This finding indicates that the inducer attracted the numerosity perception of the reference stimulus presented in a different modality, suggesting the presence of cross-modal serial dependence.

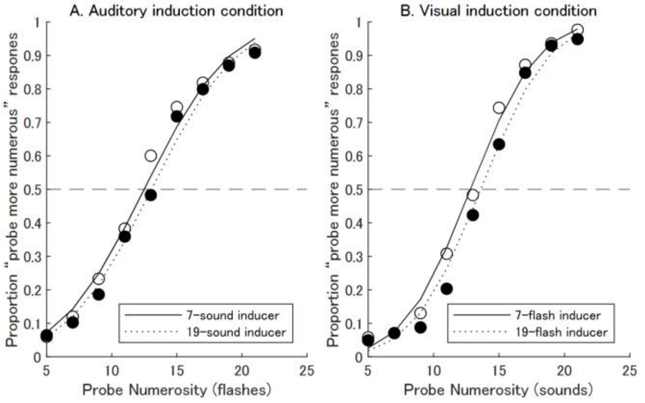

Figure 3. Psychometric functions fitted to the data from all participants. (A) Psychometric functions for each numerosity of inducer in the auditory induction condition. (B) Psychometric functions for each numerosity of inducer in the visual induction condition.

To examine the results more precisely, we tested whether the PSE differed for each participant between inducers with many and few elements. Significant differences were observed in both the auditory induction condition ($t(34) = 2.61$, $p = .013$, $dz = 0.33$) and the visual induction condition ($t(34) = 4.42$, $p < .001$, $dz = 0.69$), indicating that the PSE of the reference stimulus was higher when preceded by an inducer with a larger number of elements (Figure 4). Regardless of the modality in which the inducer presented, cross-modal serial dependence was observed.

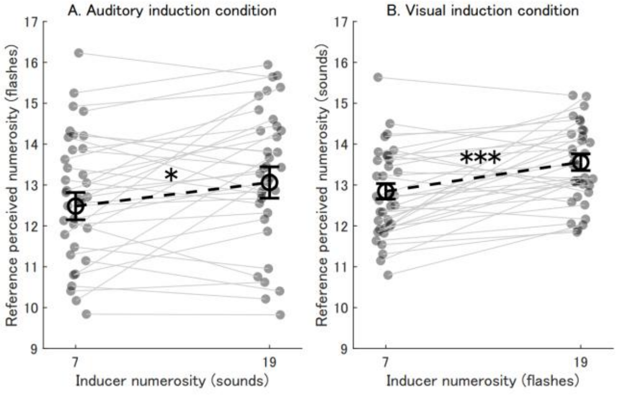

Figure 4: PSE values for each participant (gray circles) and their mean (white circles). (A) Auditory induction condition. (B) Visual induction condition. Error bars represent the standard error of the mean (SEM). *n.s.* = not significant, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$

We then examined whether the serial dependence effect was consistent within individuals across the auditory and visual induction conditions. Figure 5 shows a scatter plot of the serial dependence effects for both conditions. No significant correlation was observed between the serial dependence effects under the two conditions (ρ = –0.03, p = .850), suggesting that the effect was not consistent within individuals across modalities.

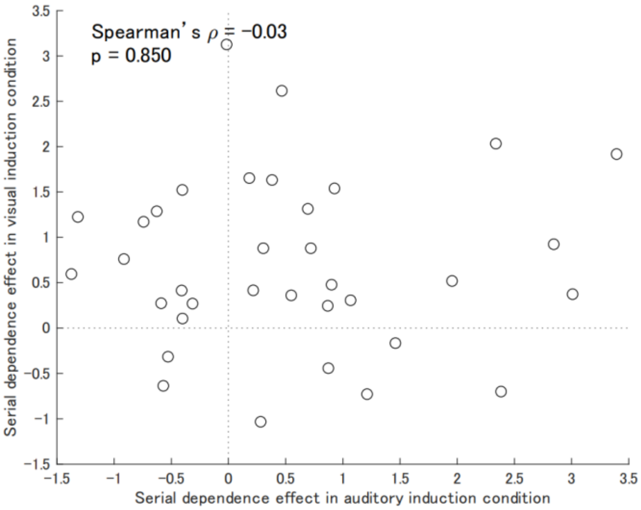

Figure 5: Scatter plot of individual serial dependence effects across the visual and auditory induction conditions.

The mean proportion of correct responses (± SEM) in catch trials was 81% ± 3% in the auditory induction condition and 74% ± 4% in the visual induction condition. This suggests that participants maintained sufficient attention to the induction stimuli throughout the experiment. The correct rate for catch trials was significantly higher in the auditory induction condition ($t(34) = 2.25$, $p = .031$).

Discussion

We examined whether cross-modal serial dependence occurs in order to investigate the processing stages involved in serial dependence in numerosity perception. A previous study (Fornaciai & Park, 2019) showed the absence of a cross-modal effect from a sequence of tones to dot arrays. However, it remained unclear whether cross-modal effects occur when the presentation format was unified to sequences of sounds and flashes. Our results showed that serial dependence emerged in both directions between vision and audition.

The presence of serial dependence across modalities suggests the involvement of a modality-independent and abstract representation of numerosity. Abstract numerical representations are found in the parietal and frontal cortices (Eger et al., 2003; Nieder, 2012, 2016; Piazza et al., 2006; Togoli & Arrighi, 2021), and these regions are known to exhibit shared representations of symbolic and non-symbolic numbers (Piazza et al., 2007; Sokolowski et al., 2017). This finding aligns with evidence that symbolic numbers can induce serial dependence in non-symbolic numerosity (Fornaciai & Park, 2022).

Although our results suggest that higher-level processing stages are involved in cross-modal serial dependence in numerosity perception, the stage at which serial dependence acts may be a lower-level stage. There was no intra-participant consistency of the serial dependence effect between the auditory and visual induction conditions. If serial dependence occurred solely from a higher-level process that operates on the integrated representation of both modalities, we would expect similar effects in both conditions; thus, the results suggest that serial dependence effect is tied to modality-specific processes. A definitive interpretation requires further investigation, as test–retest reliability must be confirmed for a comprehensive analysis of individual differences in serial dependence (e.g., Kondo et al., 2022).

The view that low-level processing is involved in the serial dependence observed in the present study is consistent with findings from studies using temporally presented stimuli. Estimating numerical magnitude from temporally presented stimuli is considered to necessitate temporal frequency processing. It has been suggested that the temporal frequency of visual stimuli is processed across a wide range in the visual cortex (D'Souza et al., 2011). Thus, in the auditory induction condition, where visual perception was influenced, it is plausible that serial dependence acted on the processing stage where the visual sequence was processed in the visual cortex. Furthermore, low-frequency components corresponding to the mean on–off frequency of the stimuli in this study are known to be processed in the auditory cortex (Giraud et al., 2000). This suggests that in the visual induction condition, serial dependence may have also acted on the stage where the auditory sequence was processed in the auditory cortex. In addition, it has been reported that numerosity from temporally presented stimuli (sequences of flashes or tones) is processed in the visual and auditory cortices, respectively (Cavdaroglu et al., 2015). These findings support the view that serial dependence emerges from modality-independent higher-level processing, subsequently influencing the modality-specific processing of following stimuli in the other modality.

The fact that cross-modal serial dependence was observed in the present study with matched presentation formats, whereas it was not observed in a previous study employing different presentation formats (Fornaciai & Park, 2019), suggests that numerical processing varies with presentation format. It has been argued that the visual system processes numerosity differently depending on the presentation format, based on the accuracy and other performance metrics when comparing numerosities presented spatially or temporally (Tokita & Ishiguchi, 2012), and this is consistent with our findings. Moreover, distinct neuronal populations in the monkey intraparietal sulcus (IPS) are activated according to the presentation format (Nieder et al., 2006). Similarly, in humans, the right IPS has regions that both depend on and are independent of presentation format (Dormal et al., 2010). The observation of cross-modal serial dependence specifically under matched presentation formats, suggests that this phenomenon could be attributed to format-dependent regions of the IPS. As the IPS is one of the regions where abstract numerical representations reside, these findings support our claim that abstract numerical representations are involved in cross-modal serial dependence. Furthermore, in judgments on whether pairs of auditory and visual stimuli represent the same numerosity, a decrease in accuracy was observed only when both the modality and presentation format differed (Barth et al., 2003). This implies that the impact of presentation-format differences on numerosity processing is further amplified when the modality differs as well, a pattern that aligns with our findings.

Regarding cross-modal serial dependence, the distinction between serial dependence and repulsive bias has been discussed. Repulsive bias is thought to reflect perceptual adaptation, arising from mechanisms distinct from those underlying serial dependence. The existence of a cross-modal effect for repulsive bias (Arrighi et al., 2014; Togoli & Arrighi, 2021) has been cited as evidence that its mechanism differs from that of serial dependence. However, our results suggest that serial dependence in numerosity perception can occur across different modalities.

Although the present study demonstrated that serial dependence in numerosity perception can occur across modalities, several methodological limitations should be noted. First, stimuli of different durations were used for each modality. This adjustment was necessary to create a stimulus that allowed for a comparison task while preventing counting, all the while maintaining the same numerosity of stimulus elements. However, it is possible that differences in stimulus duration and the retention time across conditions may have affected the observed serial dependence. Furthermore, serial dependence effect is known to be strongly affected by stimulus uncertainty (Ceylan et al., 2021; Gallagher & Benton, 2024; Kim & Alais, 2021), but the uncertainty of the stimuli used in this study has not been verified to be equal across modalities. In addition, one cannot assume linearity of serial dependence effects when measured through a comparison task involving different stimuli. Therefore, it is important to acknowledge that the present procedures do not allow for a strict comparison of serial dependence effect across different conditions. Although our results showed that the strength of serial dependence was inconsistent within individuals across conditions, verification of test–retest reliability will be essential for a rigorous examination of differences between conditions and individual differences.

Conclusion

The present study examined whether serial dependence in numerosity perception extends across modalities to explore the underlying mechanism of serial dependence. The results showed that serial dependence in numerosity perception arises bidirectionally between the visual and auditory modalities, suggesting the involvement of an abstract, modality-independent representation of numerosity. Furthermore, the observation that the strength of serial dependence varied across modalities within individuals suggests that low-level processing is involved in the serial dependence observed in the present study. These results support the view that both higher- and lower-level processing are involved in serial dependence.

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