Exploring the Phenotype and Possible Mechanisms of Palinopsia in Visual Snow Syndrome

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Purpose. Palinopsia (persistent afterimages and/or trailing) is a common but poorly understood symptom of the neurological condition visual snow syndrome. This study aimed to collect a phenotypical description of palinopsia in visual snow syndrome and probe for abnormalities in temporal visual processing, hypothesizing that palinopsia could arise from increased visibility of normal afterimage signals or prolonged visible persistence.

Methods. Thirty controls and 31 participants with visual snow syndrome (18 with migraine) took part. Participants completed a palinopsia symptom questionnaire. Contrast detection thresholds were measured before and after brief exposure to a spatial grating because deficient contrast adaptation could increase afterimage visibility. Temporal integration and segregation were assessed using missing-element and odd-element tasks, respectively, because prolonged persistence would promote integration at wide temporal offsets. To distinguish the effects of visual snow syndrome from comorbid migraine, 25 people with migraine alone participated in an additional experiment.

Results. Palinopsia was common in visual snow syndrome, typically presenting as unformed images that were frequently noticed. Contrary to our hypotheses, we found neither reduced contrast adaptation ($F(3.22, 190.21) = 0.71$, $P = 0.56$) nor significantly prolonged temporal integration thresholds ($F(1, 59) = 2.35$, $P = 0.13$) in visual snow syndrome. Instead, participants with visual snow syndrome could segregate stimuli in closer succession than controls ($F(1, 59) = 4.62$, $P = 0.04$, $\eta_p^2 = 0.073$) regardless of co-occurring migraine ($F(2, 53) = 1.22$, $P = 0.30$). In contrast, individuals with migraine alone exhibited impaired integration ($F(2, 53) = 4.44$, $P = 0.017$, $\eta_p^2 = 0.14$).

Conclusions. Although neither deficient contrast adaptation nor prolonged visible persistence explains palinopsia, temporal resolution of spatial cues is enhanced and potentially more flexible in visual snow syndrome.

Keywords: temporal integration, temporal segregation, contrast adaptation, visible persistence, afterimages, trailing

Symptomatology is key to advancing understanding of visual snow syndrome (VSS), a neurological condition defined by self-reported visual symptoms.[1] A distinctive symptom is palinopsia,[1] visual images that persist despite removal of the eliciting object.[2,3] It presents as persistent afterimages of stationary objects or trailing of images behind moving objects,[1] contributes to VSS diagnosis,[1] and may even be a hallmark of the syndrome due to its high prevalence.[4,5] In VSS, symptoms conform with illusory palinopsia, a broad category presumed to represent a dysfunction in visual perception due to diffuse hyperexcitability,[6] although the affected processes remain unidentified.

We investigated this key symptom to provide novel insight into VSS. First, we collected a detailed phenotypical description using a questionnaire. Improved characterization may clarify its neural basis and aid differentiation from physiologic afterimages[1] and other causes of palinopsia.[6] Second, we used well-established behavioral vision tests to investigate potential mechanisms. Under the right circumstances, visual percepts may continue or appear after object removal due to the temporal characteristics of a normal visual system, as demonstrated by experimental measures of percepts outlasting the physical stimulus and the familiar experience of afterimages.[7] Abnormalities in such phenomena may explain palinopsia in VSS. We investigated this possibility by exploring two processes that shape the perception of visual information over time: contrast adaptation and the temporal window of integration.

Deficient contrast adaptation could cause palinopsia by increasing afterimage visibility. We measured contrast detec-

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tion thresholds before and after brief exposure to high contrast, sufficient to temporarily elevate thresholds in healthy individuals due to rapid contrast adaptation (sometimes referred to as forward masking).[8–11] Contrast adaptation optimizes vision by permitting fast adjustment to contrast differences in natural scenes with each fixation[12] and by decreasing the visibility of negative afterimages arising from adaptation to object luminance.[13–15] Theoretically, deficient contrast adaptation could permit perception of afterimage signals that would be subliminal in a normal visual system, consistent with the proposal that palinopsia may arise from pathophysiological enhancement of physiologic afterimages.[16]

Alternatively, palinopsia could represent exaggerated visible persistence, the normal phenomenon in which brief stimuli remain visible for ~100 ms despite their physical offset due to persisting neural responses.[17] Visible persistence can also cause healthy individuals to see slightly blurred trails behind moving objects, known as motion smear.[18] Visible persistence limits temporal resolution by bridging brief temporal gaps between successive stimuli, thus facilitating integration (i.e., combination) over a temporal window in early visual processing.[19,20] Stimuli falling within this window are combined into a unified percept, whereas stimuli occurring further apart in time are segregated into distinct events.[20] Therefore, we used missing-element[19] and odd-element[21] tasks to assess temporal integration and segregation, respectively. If visible persistence is prolonged in VSS, this would widen the temporal integration window by promoting integration of stimuli that a normal visual system would segregate.

Materials and Methods

Participants

In a cross-sectional study, we compared temporal integration/segregation and rapid contrast adaptation in 30 non-headache controls (mean age, 26.8 years; range, 19–42) and 31 people with VSS (mean age, 28.7 years; range, 19–42; 18 with migraine). The sample size was consistent with previous research on perceptual differences in VSS.[22,23] Twenty-five people with migraine (mean age, 29.3 years; range, 19–41) participated in a secondary experiment. All participants completed a palinopsia questionnaire.

Participants were recruited from a database of previous study participants and via advertisement within the University of Melbourne from September 2022 to September 2023. The relevant diagnostic criteria were used to classify participants with VSS[1] and migraine.[24] Controls were excluded if they reported headaches with migraine features or more than four headaches per year. Participants in the migraine and control groups were excluded if they were taking medications known to affect vision or cognition, including for migraine prophylaxis. A subset of participants with VSS were taking neuroactive medication (see Supplementary Table S1), reflecting the high prevalence of migraine,[1,5] anxiety, and depression.[25,26] Participants reported no association between VSS onset and medication use and no current intake of medications associated with palinopsia (i.e., maprotiline,[27] nefazodone,[28,29] topiramate,[30,31] or trazodone[32]). A clinical eye examination was performed to ensure best-corrected visual acuity of 6/7.5 or better, refractive error no more than ±5.00 diopter (D) sphere and 2.00 D astigmatism, normal ocular health (pupil responses, ocular motility, slit-lamp biomicroscopy examination, fundus examination), and normal visual fields (C-40 suprathreshold screening, Humphrey Field Analyzer II series; Carl Zeiss Meditec USA, Dublin, CA, USA).

Protocols were approved by the University of Melbourne Human Research Ethics Committee. Participants provided written informed consent in accordance with the tenets of the Declaration of Helsinki prior to testing. Participants attended a single 2-hour session and were reimbursed with a $20 gift voucher to defray travel costs. For those with migraine, the session took place at least 4 days after migraine, and the follow up noted migraine occurrence within 48 hours of testing.

Computer-Based Vision Testing

Stimuli were generated using custom software in Python using PsychoPy3[33] running on a desktop computer (Windows 10; Microsoft, Redmond, CA, USA) and displayed on a G90FB monitor (1280 × 1024 pixels, 36 × 27.5 cm, 85 Hz; ViewSonic, Brea, CA, USA) that was calibrated using an OptiCal luminance meter (Cambridge Research Systems, Cambridge, UK). In a dim room, participants viewed the monitor binocularly with appropriate refractive correction from a distance of 1 meter, with head position maintained by a chin rest.

Task One: Rapid Contrast Adaptation. Contrast detection thresholds were measured at baseline and at several time points following adaptation (time delays of 47, 106, 200, and 400 ms) to characterize pre-adaptation contrast sensitivity, post-adaptation desensitization, and recovery time course as per Lek et al.[11] Stimuli were presented centrally on a 68- cd/m^2 gray background. A central cross and four diagonal lines provided fixation aids. The adapter was a 2 × 2 grid of 50% contrast Gabors with a center-to-center separation of 1° displayed for 1 second. The test stimulus was a single 94-ms Gabor. Gabors were 2-cycle per degree sinusoidal gratings embedded in a Gaussian envelope with a standard deviation of 0.167°. Test and adapter Gabors were matched in orientation (horizontal or vertical) and phase (variable), which were randomly selected on each trial.

In a four-alternative forced-choice procedure, the test stimulus randomly appeared in one of four possible locations on each trial. Participants indicated its location via keypress. Trials consisted of the test stimulus (baseline condition) or the adapter followed by the test stimulus after a time delay (post-adaptation conditions) during which the background luminance was displayed (Fig. 1). Tones denoted test stimulus onset and provided feedback on response correctness. The intertrial interval of 1 second was sufficient for full recovery of contrast sensitivity.[11]

Test stimulus contrast varied according to two interleaved three-down, one-up staircases with six reversals that converged on 79% correct performance.[34] Contrast was initially 50%, and the step size was 0.2 log units for the first two reversals and 0.1 log units thereafter. A 1-minute break preceded baseline runs. There were two runs per condition, completed in a randomized order, resulting in four staircases in total per condition. The final threshold estimate was taken as the geometric mean of the thresholds from the four staircases.

Task Two: Temporal Integration and Segregation of Form. The missing-element[19] and odd-element[21] tasks assess the temporal integration and segregation of

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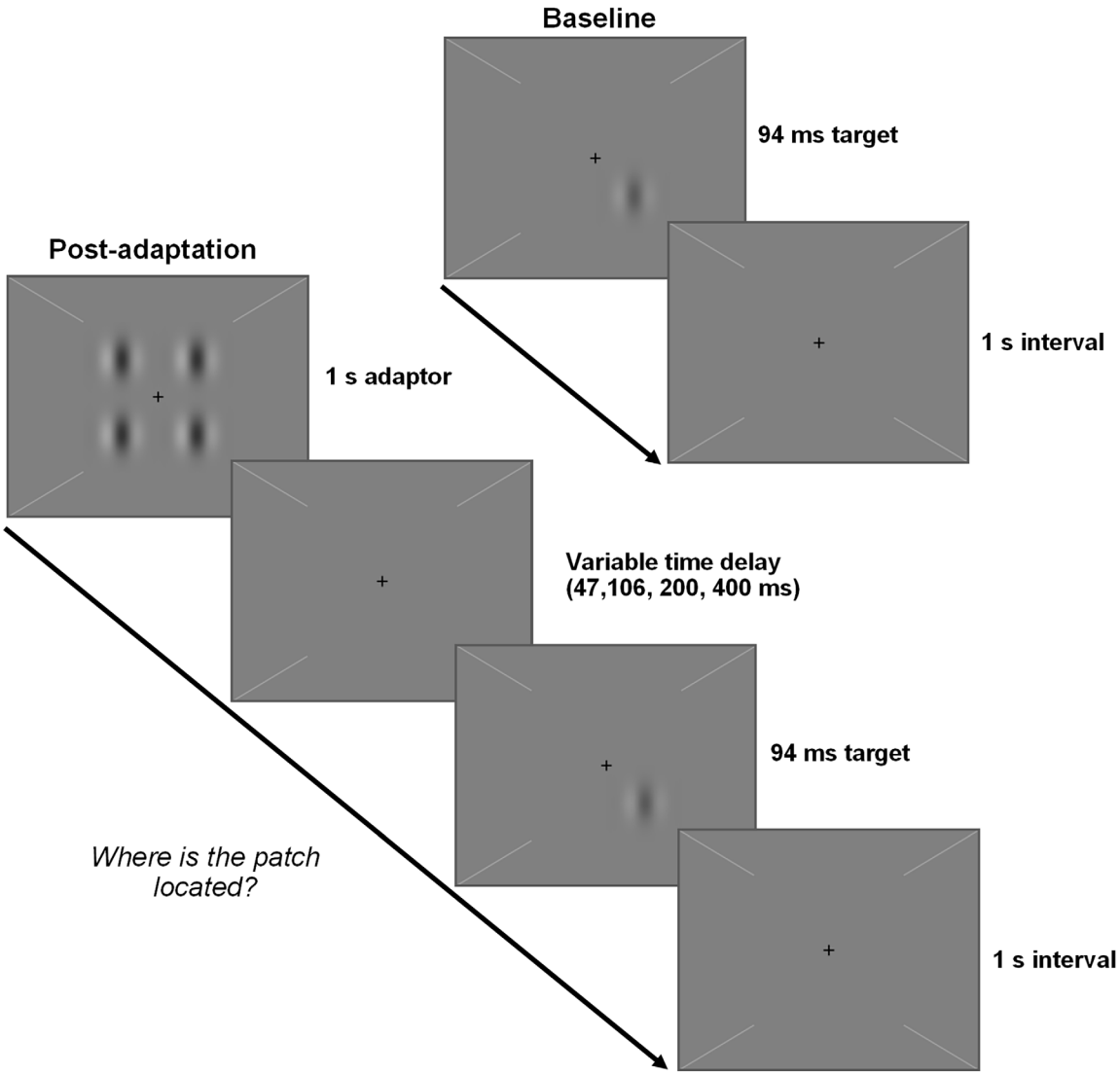

Figure 1. Trial sequence for the contrast adaptation paradigm. The test stimulus was a Gabor that appeared in one of four possible locations at a contrast that varied across trials. Trials consisted of either the test stimulus (baseline condition) or the adapter (a 2 × 2 grid of Gabors at 50% contrast) followed by the test stimulus after a time delay (post-adaptation conditions) during which the background luminance was displayed. The intertrial interval was 1 second for all conditions. Participants pressed a key to indicate the location of the test stimulus.

form cues, respectively, using the same stimuli but differing instructions. Two 12-ms images were presented successively with a variable blank interstimulus interval (ISI). Together, the images formed a 4 × 4 grid of 15 elements (0.5° element width and separation) with one unoccupied location. Elements were black 0.06°-wide annuli with a central gap randomly oriented at 0°, 45°, 90°, or 135° presented on a uniform gray background (53 cd/m^2). The first image contained half of the grid (seven elements and one half element) and the second image contained the complementary half of the grid, such that the images had a single unoccupied location in common. The location of this missing element was identifiable if the images were integrated (Fig. 2A). The grid also contained an odd element, as each image contained opposite halves of a single element at the same location that appeared as two successive half circles if the images were segregated (Fig. 2A). This odd element could not be localized if the two half circles appeared simultaneous due to temporal integration of the images. Therefore, performance on both tasks depended on the temporal separation of the images. Participants were instructed to locate missing or odd elements in separate blocks to assess integration and segregation, respectively, in counterbalanced order. Using a method of constant stimuli, nine ISIs (12, 24, 35, 47, 59, 71, 82, 94, and 106 ms) were tested 20 times across four runs that presented each ISI five times in a randomized order. Trials consisted of a 0.5-second black fixation cross, a blank period (random duration between 0.5 to 1.5 seconds in 10-ms steps), the image sequence (Fig. 2A), a 0.5-second blank period, and then a 4 × 4 grid of numbered locations. Target location (missing or odd element) was randomized on each trial. Participants selected the numbered location corresponding to the target via mouse click.

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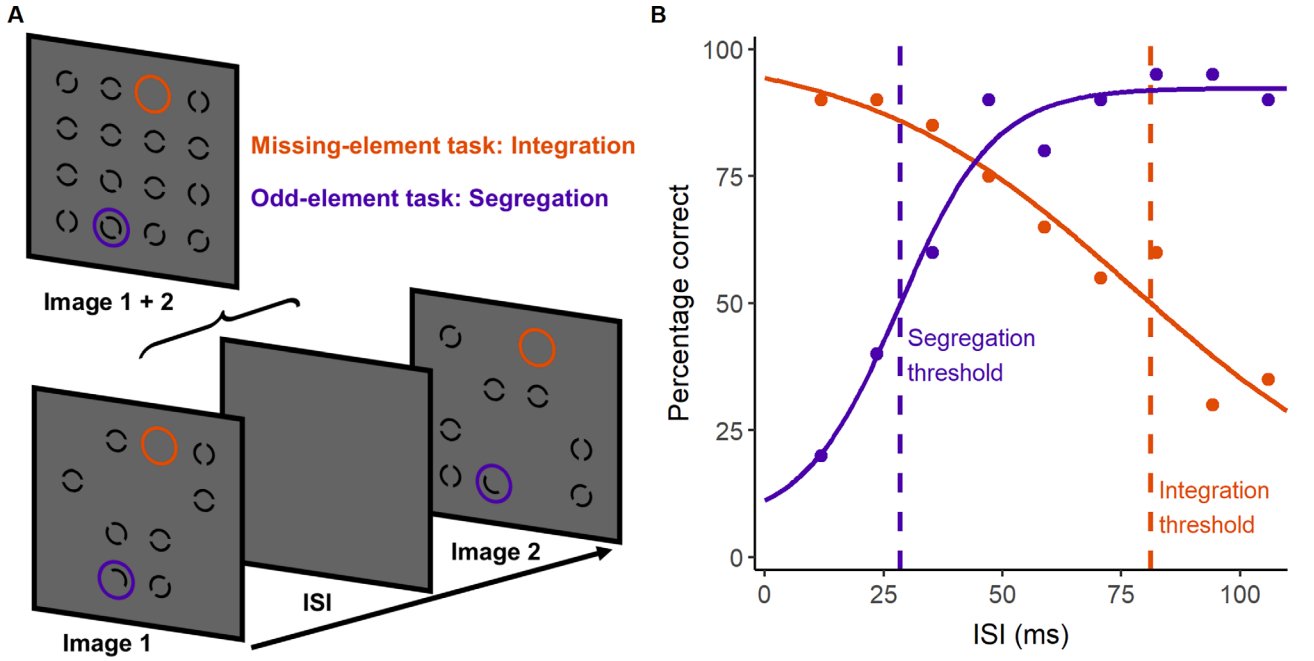

Figure 2. Paradigm for measuring temporal integration and segregation. (**A**) Illustration of task stimuli, which consisted of two successive images separated by a variable ISI. In the missing-element task (*orange*), participants located the empty location common to both images in a test of temporal integration ability. In the odd-element task, participants located the half circles in a test of temporal segregation ability. (**B**) Data (*circles*) and fitted psychometric functions (*solid lines*) for each task from an example control participant, with *dashed lines* indicating the 50% correct thresholds for integration (*orange*) and segregation (*purple*).

Performance varied in a sigmoidal fashion with increasing ISI, declining for integration[19,21] and improving for segregation[21] (see Fig. 2B). For each task, individual data were fitted with a psychometric function[35]:

$$\Psi(t) = \gamma + (1 - \gamma - \lambda) L(t, a, b) \quad (1)$$

using the R package quickpsy[36] (R Foundation for Statistical Computing, Vienna, Austria) to describe the percentage correct responses as a function of ISI (t) using a logistic function with midpoint (a) and slope (b) parameters, guess rate (γ) of 1/16, and a variable lapse rate (λ).

The threshold was taken as the ISI corresponding to 50% correct responses, giving the shortest interval for successful segregation on the odd-element task and the longest interval for successful integration on the missing-element task. The integration threshold from the missing-element task has classically been used to measure visible persistence of the first image[37,38] and applied in clinical populations.[37,39–41] Although metacontrast masking of elements in the second image by spatially adjacent elements in the first image shortens thresholds,[38,42,43] the use of 0.5° element spacing[38] as per recent studies[21,44,45] should minimize this effect. The odd-element task has also been used in clinical populations,[44,46] as it is an established measure of temporal resolution that is complementary to the missing-element task.[21,45,47–49] An abnormally wide temporal integration window would push both missing- and odd-element task thresholds toward longer ISIs, as participants would integrate over longer intervals but need greater temporal separation to segregate. Note that these tasks do not assess iconic memory (i.e., stored information about stimulus properties), as it is continued stimulus visibility rather than recollection of spatial information that determines performance.[17] The slope parameter b indicates the steepness of the psychometric function. Lower values denote a shallower slope, indicative of greater response variability and potentially suggesting impaired top–down control of visual temporal resolution.[44]

Palinopsia Questionnaire

The questionnaire screened for persistent afterimages (Part A; Supplementary Fig. S1) and trailing (Part B; Supplementary Fig. S2) and, if present, collected a detailed description using multiple-choice and free text responses. This exploratory questionnaire was codesigned with an individual with VSS based on symptom descriptions in the literature[6] and existing questionnaires for migraine[50] and refined following pilot testing in five individuals.

Statistical Analysis

Analyses were conducted in SPSS Statistics 29 (IBM, Chicago, IL, USA). Log contrast detection thresholds were analyzed via a repeated-measures analysis of variance (ANOVA) with condition (baseline and four post-adaptation delays) and group (controls, VSS) as factors. For temporal integration/segregation, thresholds and psychometric function slopes were analyzed via separate repeated-measures ANOVAs with task (integration, segregation) and group (controls, VSS) as factors. Absolute values were analyzed for slopes, which were negative for the integration task and positive for segregation task (see Fig. 2B).

A supplementary analysis examined the influence of co-occurring migraine on contrast adaptation and temporal integration/segregation by calculating z-scores, referenced to controls, for VSS subgroups with and without

migraine and an additional group with migraine alone. The z-scores were used so any differences between migraine and VSS subgroups could be related to control performance. A z-score of zero indicates performance comparable to that of the controls, whereas positive and negative scores indicate values higher and lower than the control group mean, respectively. Contrast detection thresholds, integration/segregation thresholds, and integration/segregation slopes were compared among participants with migraine alone, VSS alone and VSS and migraine via separate repeated-measures ANOVAs.

Results

Contrast Adaptation Is Normal in VSS

Contrast detection thresholds were elevated at 47 ms post-adapter and gradually recovered with increasing post-adaptation delay, with a main effect of delay ($F(3.22, 190.21) = 510.97$, $P < 0.001$, $\eta_p^2 = 0.90$; Fig. 3A), reaching near baseline levels at 400 ms, consistent with the time course of rapid contrast adaptation.[11] VSS affected neither baseline contrast sensitivity nor the degree and temporal course of contrast adaptation, as there was no significant effect of group ($F(1, 59) = 0.85$, $P = 0.36$) or interaction between group and post-adaptation delay on thresholds ($F(3.22, 190.21) = 0.71$, $P = 0.56$; Fig. 3A). A supplementary analysis using z-scores (referenced to control thresholds for each post-adaptation delay) revealed that contrast adaptation was comparable in participants with migraine alone and VSS subgroups with and without migraine, as there was no effect of group ($F(2, 53) = 0.36$, $P = 0.70$) or interaction between group and post-adaptation delay ($F(6.62, 175.37) = 1.29$, $P = 0.26$; Fig. 3B).

Temporal Integration and Segregation Are Anomalous in VSS

We hypothesized that prolonged visible persistence in VSS would widen the temporal integration window, shifting integration and segregation thresholds toward longer ISIs. Contrary to our hypothesis, there was no effect of group on thresholds ($F(1, 59) = 0.16$, $P = 0.69$) but rather an interaction between task and group ($F(1, 59) = 6.92$, $P = 0.01$, $\eta_p^2 = 0.11$; Fig. 4A).

In both groups, segregation performance rose to threshold levels at ISIs for which integration performance was still suprathreshold (see Fig. 2B), resulting in lower thresholds for segregation compared to integration, with a main effect of task ($F(1, 59) = 508.49$, $P < 0.001$, $\eta_p^2 = 0.90$; Fig. 4A). This effect was exaggerated in VSS, as group means were increased for integration but decreased for segregation relative to controls (Fig. 4A). Simple effect analysis revealed that segregation thresholds were lower in VSS compared to controls ($F(1, 59) = 4.62$, $P = 0.04$, $\eta_p^2 = 0.073$) but integration thresholds were comparable between groups ($F(1, 59) = 2.35$, $P = 0.13$). VSS participants therefore demonstrated enhanced temporal resolution of stimuli presented in rapid succession but maintained the ability to combine information over time.

Psychometric function slopes were steeper for the segregation task compared to the integration task, with a main effect of task ($F(1, 59) = 57.78$, $P < 0.001$, $\eta_p^2 = 0.50$; Fig. 4B). There was an effect of group ($F(1, 59) = 6.55$, $P = 0.01$, $\eta_p^2 = 0.10$) and an interaction between task and group ($F(1, 59) = 7.13$, $P = 0.01$, $\eta_p^2 = 0.11$), as VSS participants had steeper slopes for the segregation task compared to controls, for a simple effect of group ($F(1, 59) = 7.04$, $P = 0.01$, $\eta_p^2 = 0.11$; Fig. 4B) but similar slopes for the integration task ($F(1, 59) = 0.18$, $P = 0.67$). A supplementary analysis indicated that performance differences between groups were not driven by lapse rates. Although lapse rates were slightly higher for the segregation task ($F(1, 59) = 98.47$, $P < 0.001$, $M_D = 0.05$ [0.04–0.06]), there was no effect of group ($F(1, 59) = 0.282$, $P = 0.60$) or interaction between task and group ($F(1, 59) = 1.12$, $P = 0.29$).

Co-occurring Migraine Does Not Explain Anomalous Temporal Processing in VSS

In a secondary experiment, we determined whether migraine influenced integration or segregation performance by comparing z-scores (referenced to controls) for participants with migraine alone, VSS alone, and both conditions. A migraine 24 hours post-testing was reported by one participant, who had migraine without VSS.

For thresholds, group differences in z-scores were task specific (Fig. 5A), as there was a main effect of task ($F(1, 53) = 9.00$, $P = 0.004$, $\eta_p^2 = 0.15$), an interaction between group and task ($F(2, 53) = 5.78$, $P = 0.005$, $\eta_p^2 = 0.18$) but no main effect of group ($F(2, 53) = 1.58$, $P = 0.22$). Simple effect analysis revealed group differences in integration ($F(2, 53) = 4.44$, $P = 0.017$, $\eta_p^2 = 0.14$) but not segregation thresholds ($F(2, 53) = 1.22$, $P = 0.30$). Therefore, enhanced segregation in VSS compared to controls did not reflect the high prevalence of co-occurring migraine in VSS participants. Upon Bonferroni-corrected multiple comparisons, VSS subgroups had comparable z-scores for integration thresholds ($M_D = -0.15$; range, –1.14 to 0.84; $P = 1.0$) that tended toward positive values (Fig. 5A), suggestive of performance equal to or better than controls (Fig. 5A). Conversely, the migraine group mean z-score was negative for integration thresholds (Fig. 5A) and significantly lower than the VSS subgroup with migraine ($M_D = -0.93$; range, –1.77 to –0.10; $P = 0.024$) but not without migraine ($M_D = -0.79$; range, –1.71 to 0.14; $P = 0.12$). This suggests that migraine and VSS have opposing effects on integration thresholds.

Psychometric function slopes were unaffected by migraine diagnosis, as z-scores showed no effect of group ($F(2, 53) = 0.95$, $P = 0.40$) or interaction between task and group ($F(2, 53) = 0.75$, $P = 0.48$). The z-scores were higher for the segregation task, with main effect of task ($F(1, 53) = 9.84$, $P = 0.003$, $\eta_p^2 = 0.16$) and group means were positive (Fig. 5B), indicating a tendency for steeper segregation slopes relative to controls.

Characteristics of Palinopsia in VSS

Persistent afterimages occurred in 80.6% of VSS participants (72.2% and 92.3% of those with and without migraine, respectively) and trailing in 45.2% (44.4% and 46.2% of those with and without migraine, respectively). Palinopsia was elicited by everyday objects rather than bright lights (see Supplementary Tables S2, S3) and tended to present as indistinct afterimages of stationary objects (Fig. 6C) that preserved object outline rather than internal detail (Supplementary Table S2) or blurred and faded images trailing moving objects (Figs. 7C, 7D; Supplementary Table S3).

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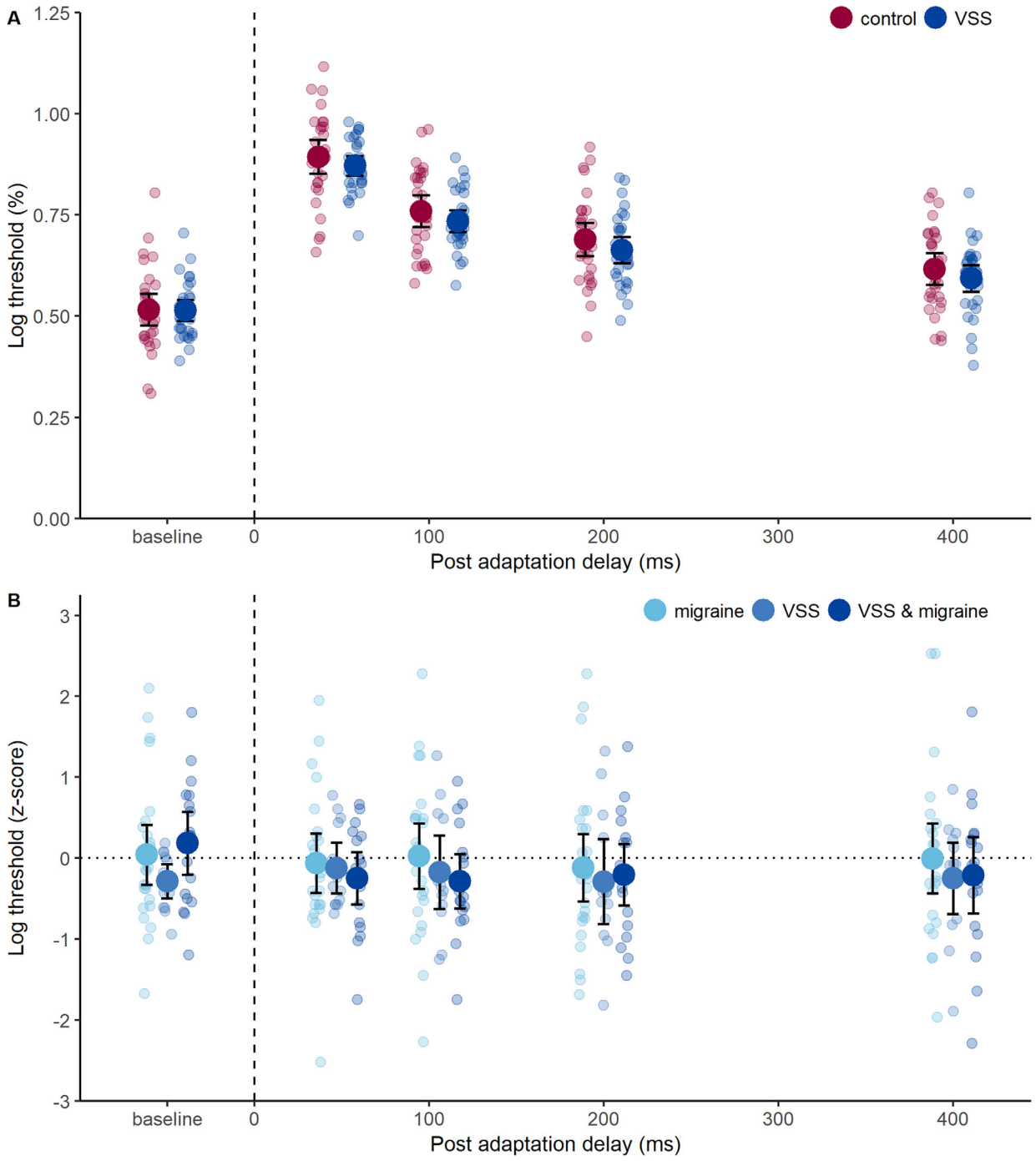

Figure 3. Performance on the contrast adaptation task. (**A**) Log contrast detection thresholds before adaptation (baseline) and at time points after adaptation, showing an initial threshold elevation and gradual recovery due to contrast adaptation in controls (*red symbols*) and participants with VSS (*blue symbols*). Group mean (*large circles*), 95% confidence intervals (*error bars*), and individual data (*small circles*) are shown. (**B**) The *z*-scores for contrast detection thresholds (referenced to controls for each post adaptation delay). Group mean (*large circles*), 95% confidence intervals (*error bars*), and individual data (*small circles*) are shown. Participants with migraine alone are indicated in *light blue*; VSS alone in *mid-blue*; and VSS and migraine in *dark blue*. A *z*-score of zero indicates that performance was the same as the control group mean. Higher *z*-scores indicate higher log contrast detection thresholds (positive for greater than control mean, negative for less than control mean).

Afterimages typically lasted 1 or more seconds (Fig. 6D) and occurred immediately after object removal in the same location. Afterimage color showed no clear predominance to be the same (i.e., positive afterimage), complementary (i.e., negative afterimage), or unrelated to the object (Fig. 6E, Supplementary Table S2).

Palinopsia typically occurred more than once a day (Figs. 6F, 7E) on a daily or near daily basis (Figs. 6G, 7F),

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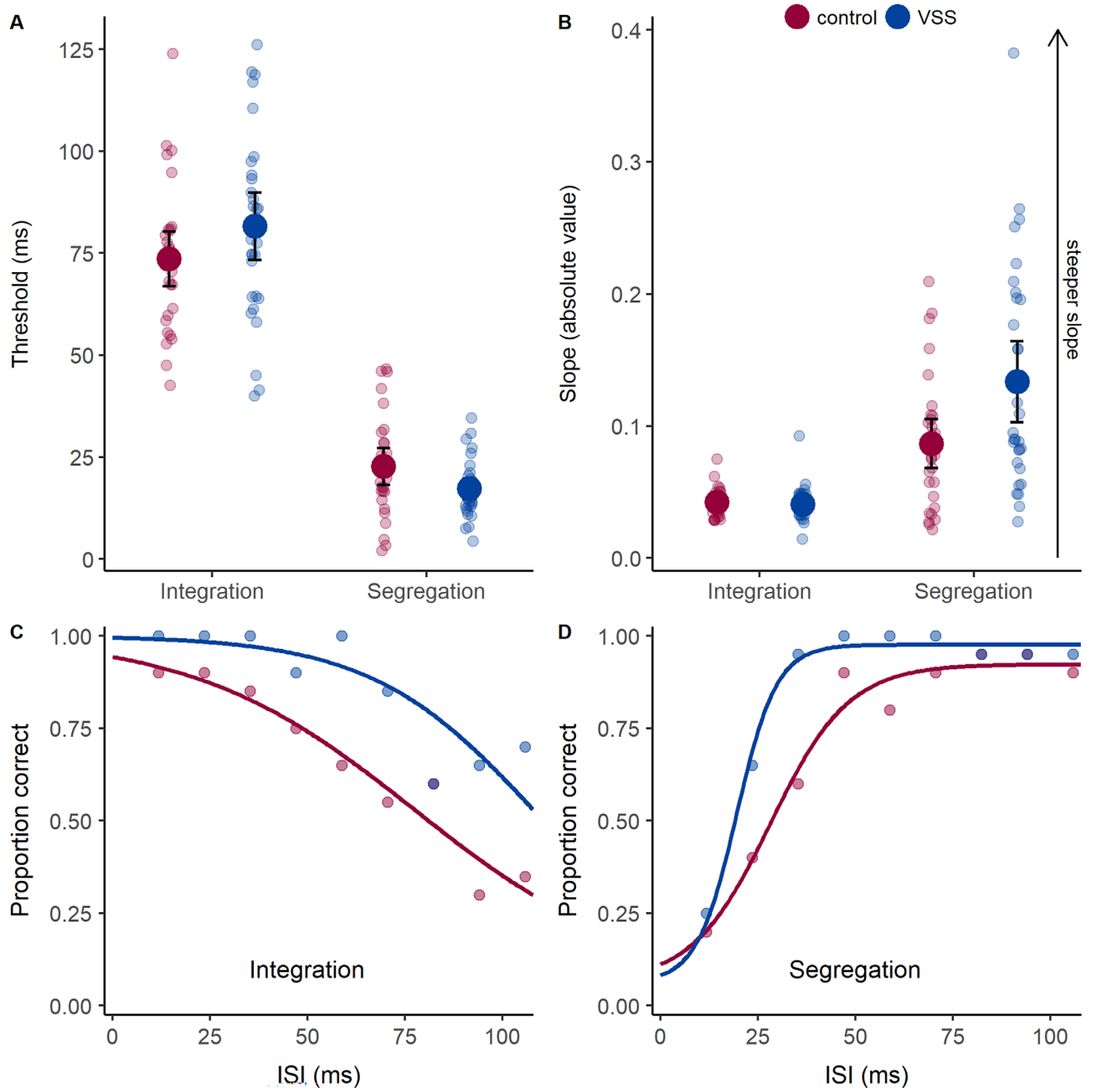

Figure 4. Performance on the missing-element (integration) and odd-element (segregation) tasks. (**A**) Thresholds indicate the ISI between images required for integration or segregation with 50% accuracy. A long threshold ISI indicates good integration ability, whereas a short threshold ISI indicates good segregation ability. (**B**) Slopes, with lower values denoting shallower slopes due to increased response variability that is indicative of greater task difficulty. Group mean (*large circles*), 95% confidence intervals (*error bars*), and individual data (*small circles*) are shown, with controls in *red* and participants with VSS in *blue*. (**C**, **D**) Example data (*circles*) and psychometric functions (*lines*) from a control participant (*red*) and VSS participant (*blue*). For segregation (**D**), note the steeper slope and leftward shift of the psychometric function in the VSS participant.

rendering any temporal association with headache difficult to interpret (Figs. 6H–6J, 7G–7I). Descriptions of typical situations did not reveal any strong associations (Supplementary Tables S2, S3).

Controls did not report palinopsia. A subset of participants with migraine alone reported persistent afterimages ($n = 5$, 20%) that occurred less frequently but did not otherwise significantly differ from afterimages in VSS (see Supplementary Table S4, Supplementary Fig. S4).

Discussion

Motivated by the symptom of palinopsia, we explored rapid contrast adaptation and temporal integration/segregation in VSS. Our results indicate that neither deficient contrast adaptation nor significantly prolonged visible persistence explains this symptom. Unexpectedly, segregation was better in VSS compared to controls, indicative of heightened temporal resolution of complementary form cues.

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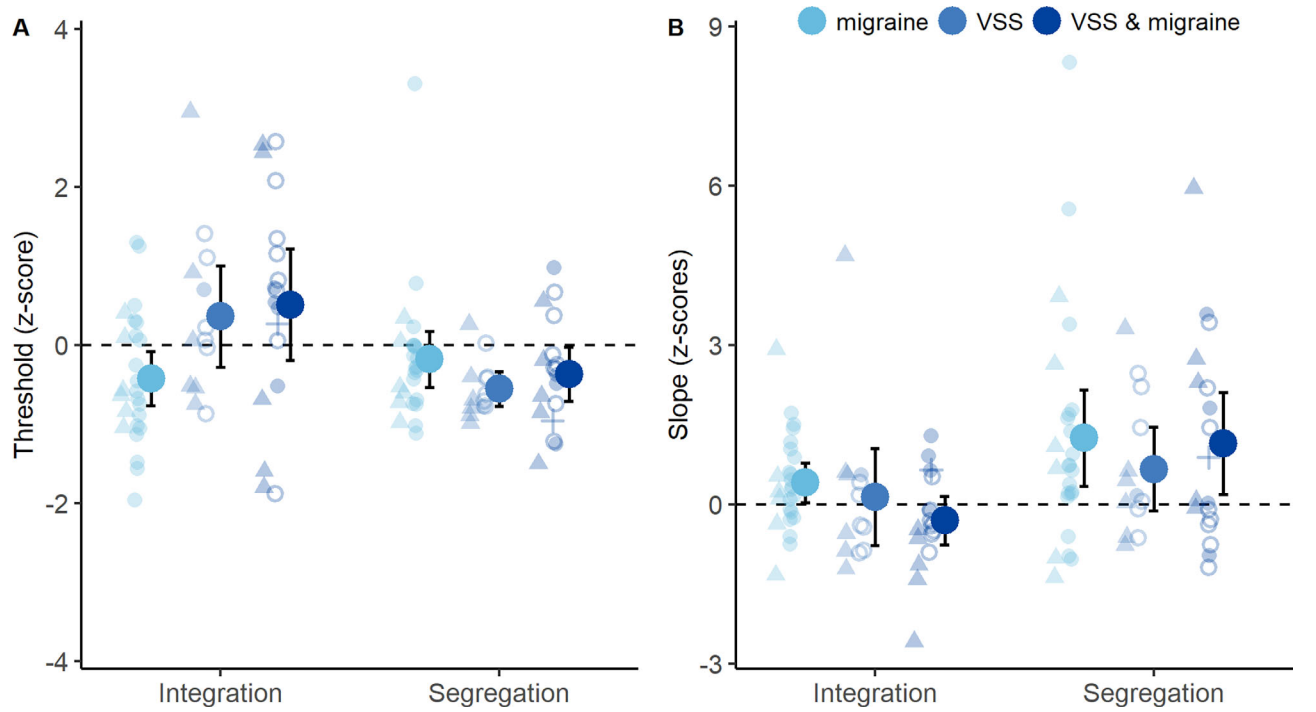

Figure 5. Influence of migraine on integration and segregation performance. (**A**) The *z*-scores for thresholds, referenced to controls. (**B**) The *z*-scores for slopes, referenced to controls. Group means (*large circles*), 95% confidence intervals (*error bars*), and individual data are shown. Participants with migraine alone are indicated in *light blue*; VSS alone in *mid-blue*; and VSS and migraine in *dark blue*. Individual data symbols indicate participants with afterimages alone (*triangles*), trailing alone (*cross*), both trailing and afterimages (*unfilled circles*), or no palinopsia (*filled circles*). A *z*-score of zero indicates that performance was the same as the control group mean. Higher z-scores indicate higher threshold or slope values (positive for greater than control mean, negative for less than control mean).

Improved temporal resolution in VSS is a novel finding with pathophysiological implications. First, rapid segregation of complementary form cues in VSS may represent an isolated or generalized enhancement of temporal resolution. Our finding may only generalize to similar tasks, as the visual system integrates input over multiple temporal windows that range from short to prolonged.[20,51] Assessment of temporal segregation via different tasks and over different time scales may be a useful avenue for future research. Second, convergent evidence suggests,[52] but does not conclusively demonstrate,[53] that healthy individuals with wide temporal integration windows on many visual tasks have a slower frequency of alpha-band neural oscillations (and, conversely, individuals with better temporal resolution have faster alpha frequencies). Thalamocortical dysrhythmia is thought to slow resting-state alpha oscillations[54,55] with a concurrent increase in gamma activity[54,56] in many conditions, including a proposed role in VSS.[57,58] Reports of decreased alpha power (i.e., less neural activity at this frequency)[59] and increased gamma power[57] in VSS are compatible with this theory. However, in this study, VSS participants did not exhibit a wide temporal integration window, a finding that is inconsistent with significantly slowed alpha oscillations but in keeping with recent reports of normal alpha frequency at rest[59] and during visual stimulation.[57]

Third, enhanced segregation (i.e., lower thresholds) with reduced response variability (i.e., steeper slopes) is unaccompanied by impaired integration in VSS. This is intriguing, given that missing-element and odd-element tasks are widely considered reciprocal expressions of a temporal integration window.[21,44–49] One consideration is that this is a somewhat simplified interpretation, as thresholds are not strongly correlated across missing-element and odd-element tasks,[45] and missing-element localization operates partially in parallel to awareness of temporal discontinuity.[60–62] Another consideration is the capacity for endogenous (i.e., goal-driven) control of temporal integration windows. Such flexibility is useful, because natural vision requires both the segregation and integration of information over time to detect change and accumulate information, respectively.[20,63,64] Small shifts in alpha frequency prior to a visual task[45,49,65,66] are proposed to be an adaptive means of optimizing temporal resolution within an individual.[67] As such, a slightly increased alpha frequency in preparation for the odd-element compared to missing-element task is thought to indicate endogenous modulation of temporal resolution[45,49] that is further accentuated by endogenous spatial attention.[49] Therefore, our results suggest greater facility to adaptively increase temporal resolution to meet task demands in VSS. Further research is needed to directly link temporal segregation performance in VSS to endogenously driven shifts in alpha frequency. However, people with VSS exhibit increased functional connectivity between V5 and regions of the dorsal attention network[68] involved in endogenous attention[69,70] and more rapidly deploy endogenous spatial attention.[71]

Integration thresholds did not distinguish between participants with and without VSS due to interindividual variation. Although the tendency for long integration thresholds suggests a subtle prolongation of visible persistence in VSS, this is not sufficient to explain palinopsia because it is unlikely to significantly smear moving objects. It is

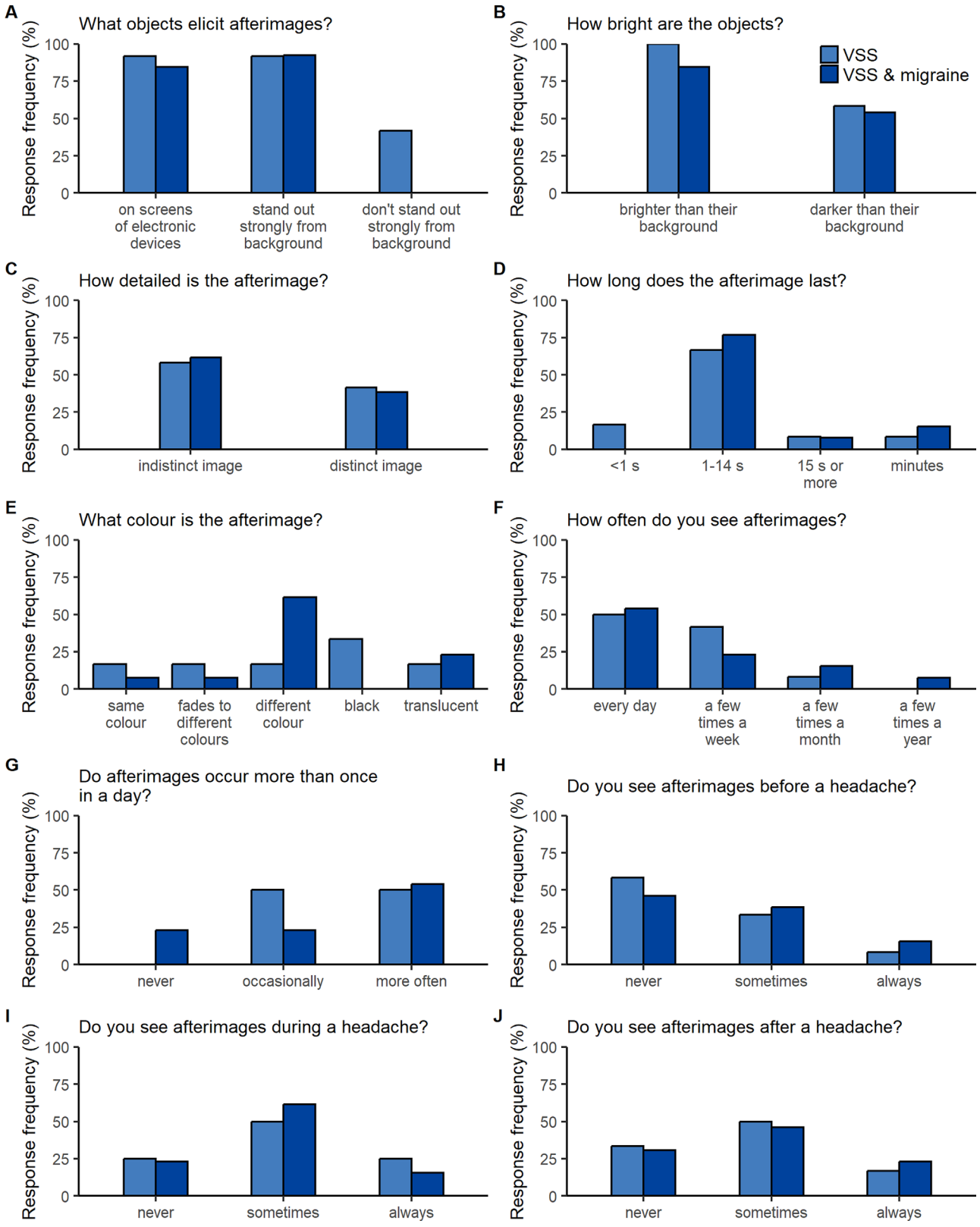

Figure 6. Characteristics of persistent afterimages in people with VSS. (**A–J**) For each question, the frequency with which each response option was selected is shown for those with afterimages who had VSS alone (*light blue*) and VSS and migraine (*dark blue*). Questions and responses are abbreviated (see Supplementary Fig. S1 for full text).

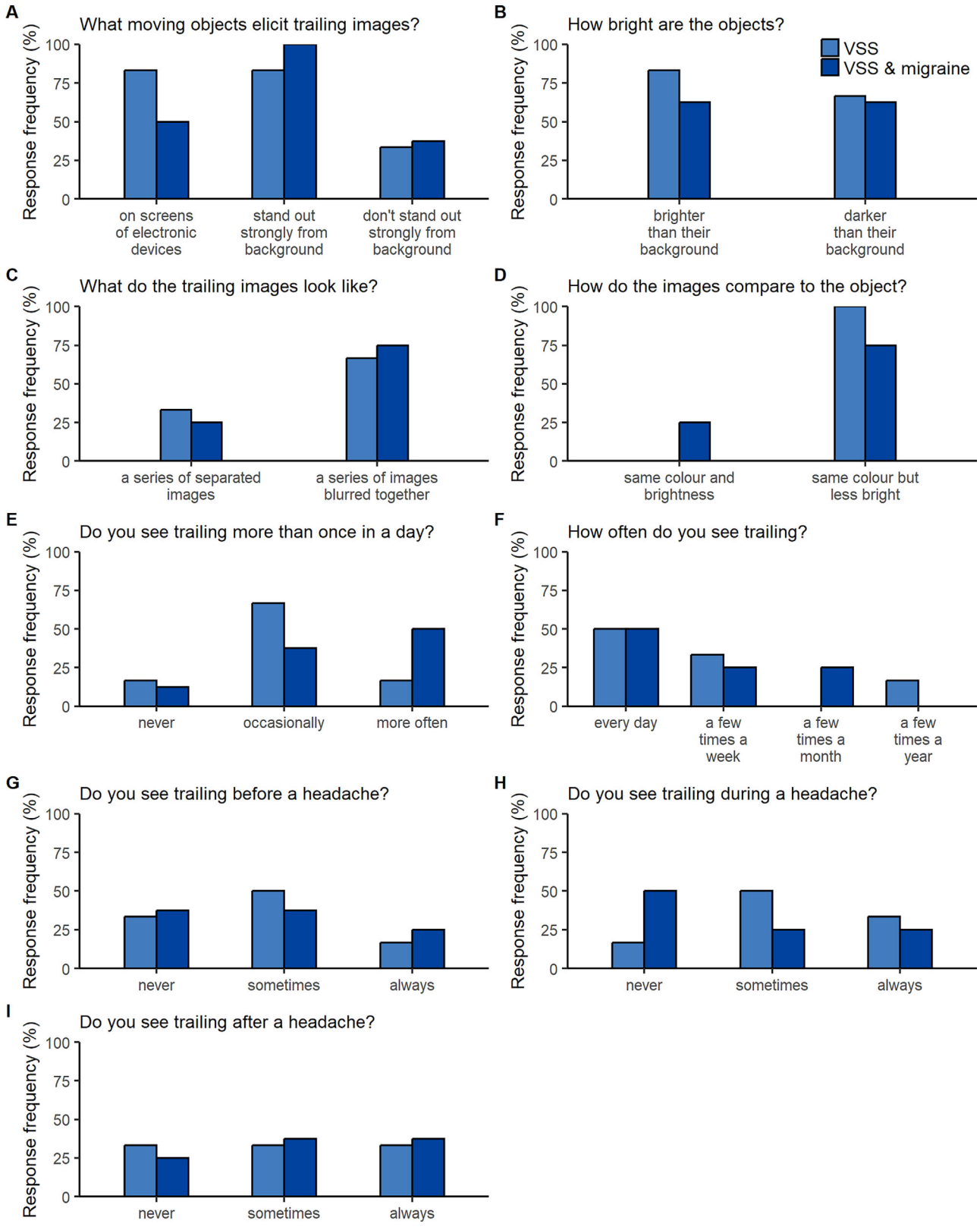

Figure 7. Characteristics of trailing in people with VSS. (**A–I**) For each question, the frequency with which each response option was selected is shown for those with trailing who had VSS alone (*light blue*) and VSS and migraine (*dark blue*). Questions and responses are abbreviated (see Supplementary Fig. S2 for full text).

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also incompatible with self-reported afterimage duration via questionnaire, which was typically longer than the longest interstimulus interval tested, suggesting that palinoptic afterimages did not aid missing-element localization.

Questionnaire results provide guidance on the differential diagnosis of palinopsia in VSS. Palinoptic afterimages are known to occur in ~10% of those with migraine,[50,72] and it has been unclear whether these are similar to afterimages in VSS, as migraine commonly co-occurs with VSS[1,5] and increases the likelihood of palinopsia.[73] Our results suggest that a minority of people with migraine experience indistinct afterimages that are qualitatively similar to those in VSS but are noticed less frequently. Palinopsia is also common in hallucinogen-persisting perception disorder, in which symptoms experienced with hallucinogenic intake later reoccur[74] and can be similar to VSS.[5] Past use of the hallucinogen lysergic acid diethylamide (LSD) is associated with both positive and negative afterimages,[75] similar to those reported by VSS participants in this study. Trailing associated with past LSD use is reported to appear as discrete images,[76] whereas VSS participants in this study generally reported trailing that looked like a series of images blurred together.

Questionnaire results confirm the presumption that persistent afterimages in VSS fit the illusory category of palinopsia.[6] Participants described afterimages that lacked the realistic clarity of hallucinatory palinopsia and are therefore unlikely to represent a dysfunction in visual memory.[6] Questionnaire responses also suggested that persistent afterimages in VSS potentially share some of the qualities of physiologic afterimages. Persistent afterimages were commonly indistinct and occurred immediately in the same location as the object, like physiologic afterimages.[6] Physiologic afterimages are typically negative[6] but can also be positive[3,6,77] and may exhibit a flight of colors.[3,6,78] Palinoptic and physiologic afterimages were not clearly distinguishable on the basis of color, as VSS participants described palinoptic images that were the same color as the object (including fading to different colors) or a different color (not necessarily complementary). However, people with VSS were not simply reporting physiologic afterimages experienced by those with normal vision. Critically, the key distinction between physiologic afterimages and palinopsia in VSS was that the latter was more readily induced, as persistent afterimages were elicited by everyday objects (e.g., people, furniture, trees) that are not expected to provoke physiologic afterimages in a normal visual system (see Supplementary Table S2).

This ready induction of persistent afterimages in VSS is consistent with the proposal that some cases of palinopsia may represent a pathological enhancement of physiologic afterimages.[16] Preliminary evidence suggests that the strength of physiologic afterimages is normal in people with visual snow and palinopsia, suggesting that afterimage generation is not enhanced.[79] However, the everyday objects that elicit palinopsia in VSS are expected to produce only weak afterimage signals that would be subliminal in a normal visual system. Contrast adaptation was normal in VSS, so our results suggest that these weak afterimage signals are not perceptible due to diminished contrast adaptation. Instead, afterimages could reach conscious perception in VSS due to a failure of mechanisms that would normally suppress weak afterimage signals in natural vision, such as conflicting contours.[80,81] Likewise, visual snow itself potentially arises from impaired filtering of pre-cortical neural noise[82,83] and not the generation of excessive spontaneous neural activity,[23] suggesting that both symptoms may represent deficient inhibition of visual input that would be subliminal in a normal visual system.

In summary, palinopsia is a common symptom of VSS that is typically experienced with high frequency by affected individuals. Although the neural basis of palinopsia in VSS remains unresolved, we ruled out both deficient contrast adaptation and increased visible persistence as an explanation. Intriguingly, our results suggest an enhanced capacity to flexibly combine or separate successive stimuli with complementary form cues depending on task goal in VSS. Consequently, further investigation of visual temporal resolution and attentional control may advance our understanding of how VSS affects visual processing.

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