Working Memory Selectively Modulates Subjective Perception: A Pilot Study

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Abstract

This study aimed to investigate how working memory interacts with perception at the behavioral level. We examined whether working memory modulates subjective perception when the general capacity for perceptual processing is kept constant. This possibility is in part motivated by the neuropsychological phenomenon of blindsight, in which subjective perception and general perceptual capacity are dissociated. To test this, in this pilot study ($n = 8$), we manipulated the congruency between perceptual and working memory content and examined its effects on sensitivity in a Yes/No (Y/N) detection task. To match perceptual processing capacity across conditions, we titrated stimulus contrast in a two-interval forced choice (2-IFC) task. There was a trend that working memory selectively modulated subjective perception, as measured by detection sensitivity (d_a) in the Y/N task, even though processing capacity in the 2-IFC task was matched. Specifically, when the working memory content was categorically incongruent with the perceptual stimulus, Y/N sensitivity was selectively impaired. These preliminary findings suggest that working memory modulates subjective perception in ways that are less general than some other manipulations, such as visual masking, which generally impairs both objective and subjective aspects of perception. We hereby treat this preprint as a form of pre-registration, specifying our hypotheses, experimental designs, and analysis methods before examining whether the preliminary results will be confirmed in a larger sample.

Introduction

Working memory engages overlapping neural mechanisms with perception, particularly within early visual areas such as V1 and V2 (Albers et al., 2013; Christophel et al., 2017). Neuroimaging studies (e.g., Gayet et al., 2017) have shown that maintaining the working memory contents enhances neural responses in the visual cortex when subsequent sensory input matches the memorized representation (a congruent stimulus). Given the shared neural mechanism, we may expect that working memory would likewise influence perception at the behavioral level.

Previous studies (Kang et al., 2011; Teng & Kravitz, 2019) have indeed shown that visual working memory not only actively interacts with early perceptual processing but can also bias subsequent perception. For example, Kang et al. (2011) demonstrated that participants who maintained a certain dot motion direction in working memory perceived subsequent motion stimuli as shifted away from the remembered direction—known as a repulsion effect. Similarly, Teng and Kravitz (2019) suggested that similarity between the content of the working memory and the perceptual task (i.e., color and orientation) systematically increased the degree of perceptual bias. Taken together, working memory can modulate perceptual processing.

However, it is unclear whether working memory mainly influences the general capacity for distinguishing between different stimuli, or whether it selectively influences the subjective experience of seeing. To address this question, we conducted a psychophysical experiment comparing perceptual performances in a two-interval forced-choice (2-IFC) and a Yes/No (Y/N) task, while the congruent or incongruent content was held in the working memory. In the 2-IFC task, one of two intervals contained a face stimulus, and the other contained a scrambled image matched in contrast, luminance, and size. In the Y/N task, either a face or a blank (no face stimulus) screen was presented.

Both perceptual tasks occurred during the delay of the working memory task, and the trials were equally distributed across three congruency conditions (Stimulus Congruent: SC, Category Congruent: CC, Category Incongruent: CI; see Figure 1 for further details). Congruency was defined by whether the perceptual stimuli matched the content of the working memory task. In the congruent conditions, participants memorized faces, whereas in the category incongruent condition, they memorized scenes, while the perceptual tasks involved faces. We included both stimulus- and category-congruent conditions to establish a gradient of similarity between the working memory content and the perceptual input, allowing us to distinguish image-level (SC) from broader category-level (CC) influences on perceptual decisions.

The 2-IFC task is a standard measure of processing capacity, which we can consider as a relatively objective measure. It depends on the observer’s ability to discriminate between a pair of external stimuli that is presented on every trial.

Therefore, the judgment is less likely to be influenced by subjective biases (but see Yeshurun et al., 2008). In contrast, the Y/N detection task can be considered a relatively more subjective task, as it requires a certain internal template or reference to compare with the input. Importantly, Azzopardi and Cowey (1997) found that Y/N sensitivity relative to 2-IFC was impaired in blindsight, suggesting that Y/N sensitivity may selectively track subjective (i.e., conscious) perception, at least in ways more than 2-IFC sensitivity does.

It has also been hypothesized that subjective experience may require some putative central mechanisms to distinguish internally generated representations (i.e., working memory and imagery) from incoming external perceptual inputs (Lau, 2019; Dijkstra & Fleming, 2023). Based on this hypothesis, one may expect working memory to selectively modulate subjective perception, rather than the general capacity of perceptual processing.

In this pilot study, we examined the interaction between working memory and perception at a near-threshold level to compare detection sensitivity measures between Y/N and 2-IFC tasks. Specifically, we hypothesized that the content of working memory selectively modulates subjective perception, without changing general processing capacity. That is, we predict that working memory-perception congruence will have a greater effect on detection sensitivity in the Y/N task than on 2-IFC sensitivity.

Methods

Participants

Eight students (6 females, 2 males, mean age = 22.4 years, *SD* = 2.4) from Sungkyunkwan University participated in our pilot study; all were naïve to the purpose of the study. We pre-screened individuals registered in the SONA system (Center for Neuroscience Imaging Research Participation System), using the following eligibility criteria: self-reported normal or corrected-to-normal visual acuity, no color vision deficiency, and no prior psychiatric diagnosis. All participants provided written informed consent under procedures approved by the Institutional Review Board of Sungkyunkwan University.

Apparatus

The experiment was programmed and run using PsychoPy version 2024.2.4 (Peirce et al., 2019). Visual stimuli were presented on an HP p1230 gamma-calibrated CRT monitor with a resolution of 1024 × 768 pixels at a refresh rate of 60 Hz (width: 39.37 cm (900 pixels), 8-bit color depth, standard dynamic range). A CRT display was chosen because of its high temporal precision and minimal display latency, characteristics that make it well-suited for psychophysical experiments. In a darkened room, participants viewed the stimuli on the monitor at a fixed distance of 54.1 cm, with their head stabilized on the head-and-chin rest.

Stimuli

Stimuli consisted of faces, scenes, masks, and scrambled faces, all presented to participants in grayscale, on a uniform gray background (21 cd/m²). The face images were selected from the Chicago Face Database (CFD; Ma et al., 2015; http://www.chicagofaces.org), and the scene images were from the *Scene Size x Clutter Database* (Park et al., 2015). We used a pixelwise random noise image (generated and saved in advance) as a mask, which was presented right after each 2-IFC/YN stimulus to avoid afterimages. We generated scrambled face stimuli in Python by applying the Fourier image processing phase, which scrambles the original face images into quadrants and rearranges them. Original face images (from the Chicago Face Database; Ma et al., 2015) were first converted to grayscale and cropped to remove background regions. The two-dimensional Fast Fourier Transform (FFT) of each image was then computed, and the phase spectrum was divided into four quadrants. Within each of the first and second quadrants, the phase values were randomly permuted along both the horizontal and vertical axes. The third and fourth quadrants were obtained by reflecting the permuted second and first quadrants across the horizontal axis, respectively. The permuted phase matrices were recombined with the original amplitude spectrum and inverse Fourier-transformed (IFFT) to reconstruct the scrambled images. This procedure

preserves the global amplitude (i.e., spatial frequency and luminance distribution) of the original faces while disrupting configural information. The scrambled faces, therefore, served as controls, ensuring that low-level visual properties were matched while facial identity was removed.

Visual stimuli for the working-memory task (sample and probe) were presented at four isoeccentric peripheral locations (eccentricity: 11.7° of visual angle from the center of the monitor). The face stimuli for the 2-IFC and Y/N tasks were presented at the monitor center. In each experimental block, the same stimuli were shown only once, except as required by the task condition (i.e., perceptual and one of the working memory samples had to be the same in the stimulus congruent condition).

During the main experiment, the root-mean-square (RMS) contrast of the face stimuli in the 2-IFC task was adaptively controlled using a 1-up-3-down staircase procedure (Levitt, 1971), targeting a threshold of approximately 79% correct performance (implemented using the StairHandler function in PsychoPy). The starting contrast value was 2.3% and the values were bounded between 0.005% and 14.1% on a logarithmic scale to avoid reaching zero contrast. We ran the staircase separately for each condition (SC, CC, CI; see Figure 1), and each staircase consisted of 33 trials to ensure condition-specific threshold values as well as comparable performance levels across conditions. The contrast value from the last (33rd) trial was taken as the final converged threshold, which was then used as the fixed contrast in the subsequent Y/N task under the same congruency condition.

Procedure

To examine how working memory content and its congruency systematically influence perceptual decisions, we used a 2 (perceptual tasks: 2-IFC, Y/N) × 3 (congruency: SC, CC, CI) within-subject factorial design. The experiment was conducted over two days, with three blocks (approximately 1.5h) completed per day. Each block consisted of two sub-blocks corresponding to the two perceptual tasks: the first sub-block was for the 2-IFC task, followed by the second sub-block for the Y/N task. Within each sub-block, 33 trials from each of three conditions (SC, CC, CI) were performed in random order. Participants were allowed to take an optional 5-minute break between blocks. In total, participants completed six such blocks, yielding 1,188 trials (6 blocks × 33 trials × 2 perceptual tasks × 3 congruency conditions).

On the first day, participants read the task instructions and completed 15 practice trials in the CC condition (3 trials for each: working memory task only, 2-IFC task only, Y/N task only, combined working memory-2-IFC, and combined working memory-Y/N) with trial-to-trial feedback. Feedback was shown as either “Correct” or “Incorrect”.

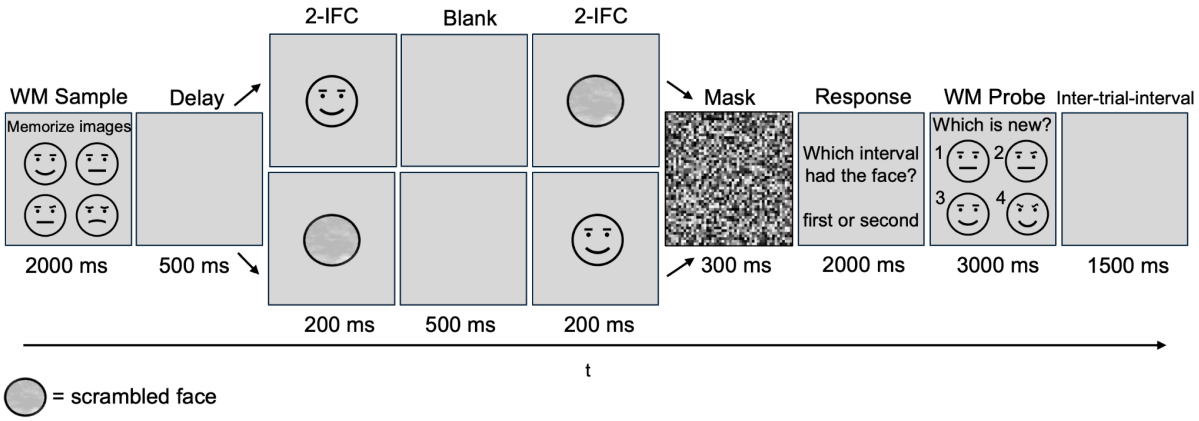
In the main experiment, participants were asked to perform either the 2-IFC or the Y/N task during the working memory delay period (Figure 1). At the beginning of each trial, as working memory sample stimuli, four different face images were

presented for 2000 ms, followed by a 500-ms delay. In the 2-IFC sub-block, two stimuli (a face and a scrambled face) were randomly and sequentially shown for 200-ms each, with a 500-ms inter-stimulus interval. Following the 300-ms mask, participants had 2000-ms to indicate whether the face appeared in the first or second interval, using left or right arrow keys.

In the Y/N sub-block, either a face or just a blank was presented in a single interval, and participants judged whether a face appeared or not. Each face stimulus was followed by a 300-ms mask.

Regardless of the perceptual task, after the first response on the perceptual task, the working memory probe was presented: one of the four images was replaced from the initial sample sets, and the participants were asked to report which was the new image using the 1, 2, 3, or 4 keys within the time limit of 3000-ms. This probe display was followed by a 1500-ms inter-trial interval. A beep sound was played when the participant did not press any keys within the time limit. Nevertheless, the response was recorded up until the appearance of a working memory sample for the next trial, even after the beep sound. In the main experiment, no feedback was provided for either the working memory or the perception task.

Stimulus Congruent Condition (2-IFC)



Stimulus Congruent Condition (Y/N)

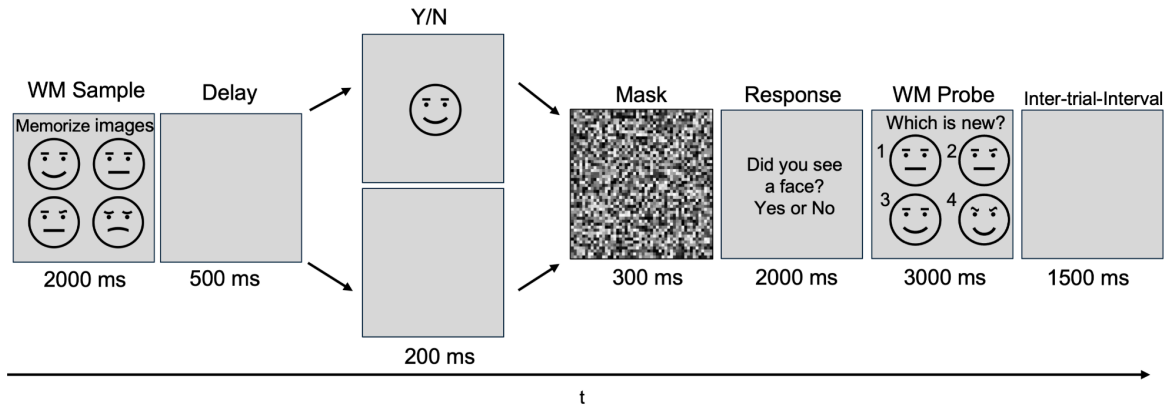


Figure 1. Experimental paradigm and task conditions *In the Stimulus Congruent (SC) condition, one of the working memory (WM) samples was physically identical to the face stimulus in the perceptual task (2-IFC and Y/N). In the Category Congruent (CC) condition, working memory stimuli belonged to the same category (faces) as the perceptual stimulus but were not physically identical. In the Category Incongruent (CI) condition, working memory stimuli belonged to a different category (scenes) from the perceptual face stimulus. Regardless of condition, a single trial consisted of a working memory sample display (encoding 4 images), a delay, a perceptual task (2-IFC or Y/N face detection), and finally a working memory probe display in which participants identified the novel stimulus. For copyright reasons, face stimuli were substituted in this manuscript with copyright-free emoji exemplars, only for illustrative purposes.*

Data Analysis

Working memory task

We calculated the accuracy for the working memory task for each of the trials accompanied by 2-IFC and the Y/N task in the delay to examine whether the working memory performance varied depending on the type of perception task.

Perception task: stimulus detection

For the perception task, we calculated detection sensitivity, i.e., participants' ability to discriminate between faces (signals) and scrambled faces (noises), and criterion, according to signal detection theory (SDT; Macmillan & Creelman, 1991). All the following analyses were based on the unequal-variance SDT model because variances for the signal and noise distributions are usually different, especially for the Y/N task.

$$d_a = \sqrt{\frac{2}{1+s^2}}\,[\Phi^{-1}(HR) - s \cdot \Phi^{-1}(FAR)],$$

where Φ^{-1} denotes the z-transformation of hit rate (HR) and false alarm rate (FAR). For the Y/N task, HR was the proportion of "Yes" responses to the signal, and FAR was the proportion of "Yes" responses to the noise:

$$HR = P(\text{"}Yes\text{"}|signal)$$
$$FAR = P(\text{"}Yes\text{"}|noise)$$

To calculate the HR and FAR for the 2-IFC task, we treated the signal in the first interval as the "signal":

$$HR = P(selecting\ the\ first\ interval \mid signal\ in\ the\ first\ interval)$$
$$FAR = P(selecting\ the\ first\ interval \mid signal\ in\ the\ second\ interval)$$

To avoid obtaining infinite z-values, 0 and 100% were adjusted by ± 0.5% prior to the z-transformation (Hautus, 1995). s represents the ratio of standard deviations of the signal and noise distribution ($s = \frac{\sigma s}{\sigma n}$). To get the estimate of s, we derived type-1 zROC (the z-transformed receiver operating characteristic function) using reaction

time (RT) data (Miyoshi et al., 2025; see Supplementary Figure 1). Capitalizing on the empirical observation that quicker RT is associated with higher confidence, we divided trials into three RT bins (fast, middle, slow) for each response type. By shifting the decision criterion across these bins, we obtained five pairs of HR and FAR. A linear function was then fitted to the resulting zROC, and s was estimated as the inverse of the slope of the best-fitting line.

Perception task: metacognition

We quantified metacognitive sensitivity, i,e, the degree to which participants discriminated between their own correct and incorrect decisions, following the meta-SDT framework (Maniscalco & Lau, 2012). Instead of collecting participants' reported confidence levels, we inferred confidence from reaction times (RT), analogous to our approach in deriving type-1 zROC. We divided trials into three confidence bins (high, medium, and low), each for correct and incorrect responses. Metacognitive sensitivity ($meta\ d_{\mathrm{a}}$) was estimated as d_a, which produces this type-2 contingency table with maximum likelihood (Maniscalco & Lau, 2012). The signal-to-noise ratio s was fixed at the value derived from type-1 zROC analysis (mentioned above) when fitting the meta-SDT model, to make the detection and metacognitive sensitivities comparable.

Lastly, metacognitive sensitivity was normalized by detection sensitivity to obtain metacognitive efficiency:

$$M_{ratio} = \frac{meta\ d_a}{d_a}$$

M_{ratio} reflects the extent to which metacognitive performance approaches the ideal level ($M_{ratio} = 1$) predicted from the individual's perceptual sensitivity. We presented it in the Supplementary Figure 2.

Results

Given the small sample size (*n* = *8*), and the nature of the experiment being just a pilot study, we did not conduct a rigorous statistical test. Instead, we reported the visual trend for the pilot. Working memory accuracy was well above chance (25%). Still, it did not reach ceiling levels regardless of the congruence condition or the perceptual task (2-IFC or Y/N) performed in the delay (Figure 2a), confirming that the participants understood and followed the task instruction reasonably well. In contrast, memory load was high enough to see the potential influence on the perceptual task. Specifically, the mean working memory accuracies accompanied by the 2-IFC task were 68.9%, 70.7%, and 72.5% for the SC, CC, and CI conditions, respectively. Working memory accuracies accompanied by the YN task were 72.7%,

73.9%, and 78%, respectively. Both showed a similar numerical trend, with accuracy gradually increasing as congruency decreased (i.e., SC > CC > CI condition).

For the perception task, the accuracies of the 2-IFC and Y/N tasks were separately shown in Figure 2b. We calibrated the stimulus contrast in the 2-IFC task targeting ~79% accuracy, and mean accuracy was actually matched across congruence conditions as we expected (SC: 81.8%, CC: 80.4%, and CI: 81.6%). The Y/N performance was above chance and lower than the 2-IFC (SC: 58.6%, CC: 56.4%, and CI: 53%).

Figure 2c indicates the converged contrast threshold obtained from the staircasing during the 2-IFC task and subsequently used for the Y/N task. The average contrast thresholds were comparable across the conditions (SC: 1.73%, CC: 1.59%, and CI: 1.71%). A repeated-measures ANOVA on the staircased contrast values showed no significant main effect ($F(2,14) = 1.227$, $p = .323$, $\eta^2 G = .036$) and Bonferroni-corrected post-hoc pairwise comparisons showed no significant differences between any pairs (SC-CC $p = .36$, CC-CI $p = .82$, SC-CI $p = 1.00$). Additionally, the 2-IFC sensitivity (d_a) did not differ across the conditions, $F(2,14) = .111$, $p = .895$, $\eta^2 G = .005$. These results show that the stimulus intensity and processing capacity were matched across the conditions.

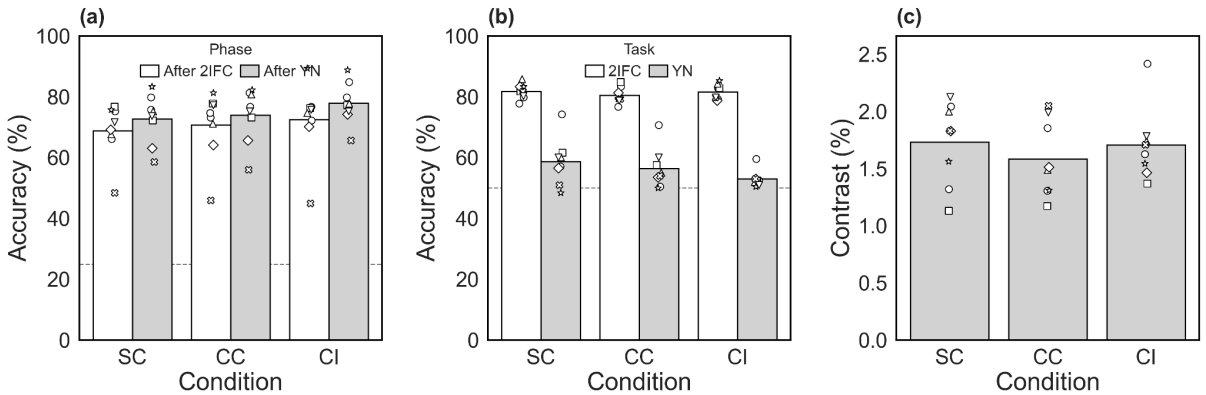


Figure 2. Group-level results of accuracy and contrast threshold *(a) Accuracies (%) of the working memory task, (b) Accuracies in the 2-IFC and YN task. (c) Average contrast thresholds derived from staircases in 2-IFC tasks.* Gray dashed lines indicate chance performance (25% for WM task; 50% for 2IFC and Y/N tasks).

Figure 3a shows the detection sensitivity (d_a) in 2-IFC and Y/N. There was a similar trend of decreasing Y/N sensitivity, whilst 2-IFC sensitivity remained consistent across conditions. We performed a one-way repeated-measures ANOVA on the YN/2-IFC detection sensitivity (d_a) ratio across congruence conditions. Although the main effect of the condition was not significant ($F(2,14) = 1.907$, $p = .185$, $\eta^2 G = .061$), we observed a weak trend in a paired t-test: lower ratios in the CI condition compared to the CC condition ($t(7) = 2.403$, *Bonferroni-corrected* $p = .142$). This result suggests that working memory may have a relatively stronger impact on

detection sensitivity in the Y/N task, supporting the notion that working memory influences more subjective tasks.

In a 2IFC task, the observer has twice as many opportunities to view the stimulus as in a yes/no task, which theoretically increases sensitivity by a factor of √2 (Macmillan & Creelman, 1991; Azzopardi & Cowey, 1997):

$$\frac{2\text{-}IFC\ d_{\mathrm{a}}}{\sqrt{2}} > YN\ d_{\mathrm{a}}$$

However, even after dividing the 2-IFC d_a by √2, it was still higher than Y/N sensitivity (SC: scaled 2-IFC d_a = 1.25, Y/N d_a = 0.87; CC: scaled 2-IFC d_a = 1.23, Y/N d_a = 0.71; CI: scaled 2-IFC d_a = 1.27, Y/N d_a = 0.44).

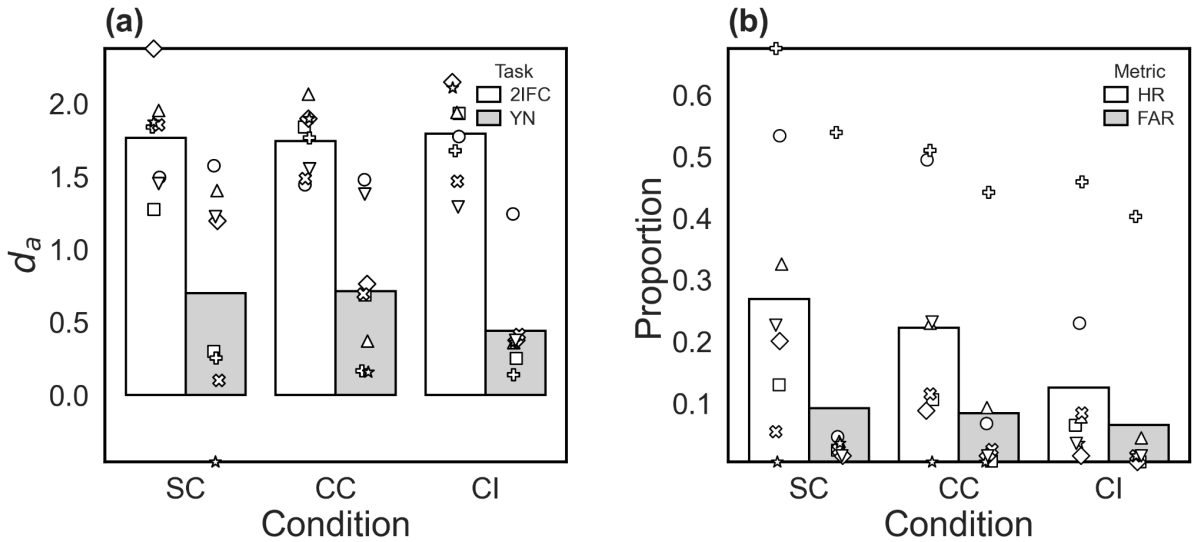


Figure 3. Group-level results of sensitivity in 2-IFC and Y/N tasks *(a) Detection sensitivity (d_a) in the 2-IFC and Y/N tasks. (b) Hit Rate (HR) and False Alarm Rates (FAR) in the YN task. Distinct markers indicate individual participants, and bar graphs indicate inter-individual averages.*

The overall trend of HR and FAR in the Y/N task was decreasing as stimuli were more incongruent (Figure 3b). This may reflect a more liberal criterion when working memory content matches the perception task condition (i.e, SC). By contrast, when the stimulus in Y/N was incongruent with the working memory, HR and FAR were the lowest (HR: 0.13, FAR: 0.06). A decreased HR and FAR may reflect a more conservative criterion when the contents from working memory and perception tasks are unmatched or conflicted (i.e, CI).

Discussion

In this study, we investigated how working memory content influences perceptual decisions and whether its effect differs for objective processing capacity and subjective experience. Because the 2-IFC contrast values were titrated to maintain a

constant accuracy for each working memory condition, processing capacity was matched. Applying these titrated contrasts to the Y/N task, therefore, allowed us to examine whether working memory modulates subjective detection independently of processing capacity. While 2-IFC accuracy and detection sensitivity (d_a) were titrated to be the same across the three different conditions, working memory selectively modulated the Y/N sensitivity (d_a). Specifically, we found a trend that d_a in the Y/N task was higher when the content of working memory was more congruent. This pattern may show that holding incongruent content in working memory harms concurrent subjective detection independently of general processing capacity. In other words, this influence of working memory on perception resembles, to some extent, the phenomenon of blindsight, in which perceptual discrimination can occur despite reduced or absent subjective experience (Azzopardi & Cowey, 1997). Such dissociation contrasts with classic visual suppression methods, such as pattern masking, which generally reduce both discrimination sensitivity and subjective perception (Knotts et al., 2018).

A closely related concept to working memory is mental imagery, which also shares neural substrates in the early visual cortex with visual perception (Dijkstra et al., 2019). However, working memory content is what we actually perceive in the recent past, whereas imagery could also refer to future and hypothetical situations. This unique relationship with perception and working memory makes it interesting to investigate how they interact and how they are distinguished from each other (Albers et al., 2013; Lau, 2022).

In the pilot study, Y/N accuracy was consistently lower than 2-IFC accuracy. This is natural because the 2-IFC task provides twice as many opportunities as the Y/N task to view the stimuli that are informative for perceptual decisions. Ideally, the 2-IFC d_a is expected to be $\sqrt{2}$ times Y/N d_a, as long as all factors are matched except for the number of stimulus presentations (Macmillan & Creelman, 1991; but see Yeshurun et al., 2008). In our data, however, even after scaling 2-IFC d_a by $\sqrt{2}$, we found that the Y/N d_a remained notably lower in all of the 3 congruency conditions—by 38% (SC), 52% (CC), 83% (CI), respectively. One possible reason is that the “noise” stimulus was not matched between the Y/N (showing a blank screen) and 2-IFC (showing a scrambled face) tasks, which may have increased temporal uncertainty in the Y/N task relative to the 2-IFC task. In the main study, we plan to use a scrambled face as the “noise” stimulus even in the Y/N task to better match stimulus and temporal predictability, thereby enabling a fairer comparison of detection sensitivity across tasks.

Another potential reason for Y/N performance falling below theoretical predictions is that whatever one holds in working memory may generally impair subjective perception, regardless of content congruency. If this is the case, the presence of concurrent working memory tasks itself should lower Y/N task performance, possibly in addition to the effect of content congruence. To test this, we will include a control condition without a working memory task to establish the baseline performance in the Y/N task.

Although the reason for low Y/N d_a remains unclear, differences in task difficulty between the Y/N and 2-IFC tasks may be a potential confounding factor that could account for the selective modulation of the Y/N task by working-memory congruency. That is, maybe the Y/N task was selectively impaired, not because it is more subjective, but simply because it was harder. In our second main experiment, we will make the Y/N task easier by calibrating only the CC condition, targeting ~79% accuracy using the staircase method. The calibrated contrast value will then be applied to the SC, CI, and new baseline conditions to examine sensitivity differences while keeping stimulus intensity matched. This manipulation adjusts the contrast in target-present trials to control for the HR, without altering task demands across congruence conditions. In this way, by increasing overall Y/N performance to a level comparable to that of the 2-IFC task, we will be able to test whether working-memory congruency selectively modulates Y/N performance, independently of task difficulty.

We performed a power analysis to obtain the sample size based on our pilot data. Assuming the common standard deviation (SD = 0.34, pooled among conditions in pilot) and repeated-measures correlation (R = .74, averaged among pairs of conditions in pilot), we simulated the power of detecting the difference in ratio (YN d_a/2-IFC d_a) we observed in the pilot (SC = 0.41, CC = 0.44, CI = 0.25) by one-way repeated-measures ANOVA (Lakens & Caldwell, 2021). We found that at least 16 participants would be necessary to have $1-\beta > .80$ to detect the observed effect at $\alpha = .05$.

We hereby treat this preprint as a form of pre-registration. To summarize, the pilot design, with the modification to use a scrambled face as the “noise” stimulus in the Y/N task, will serve as the first main experiment. In the second experiment, we will recalibrate the Y/N task to disentangle the selective effect of working memory congruency on Y/N sensitivity from task difficulty. We will recruit 16 new participants for both experiments. Individual participants will be excluded if the HR is lower than the FAR, producing a negative sensitivity index (i.e., $d_a < 0$) at least in one condition, or if the data set contains no responses in more than 20% of the whole trials. Data collection will continue until we have 16 participants who do not meet these exclusion criteria. To test our main hypothesis, we will perform one-way repeated-measures ANOVA on the YN/2-IFC sensitivity ratio across congruence conditions for both new experiments. If the main effect is found, we will continue to perform two-tailed paired t-tests to examine pairwise differences (SC-CC, CC-CI, and SC-CI); p-values will be corrected by the Bonferroni method in these post-hoc tests.

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