Modeling Visual Working Memory in Schizophrenia

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Abstract

It has been well documented that people with schizophrenia (PSZ) have deficits in visual working memory (VWM). One widely acknowledged explanation is that PSZ has decreased working memory capacity compared to healthy control subjects (HCS). Here, we leveraged the state-of-the-art computational framework – the variable precision (VP) framework to disentangle the contributions of different VWM components to the atypical behavior observed in PSZ. Using a classical delay-estimation VWM task, we found that neither the memory resources across different set size levels nor the variability at the choice stage were the differences between two groups (PSZ *vs.* HCS). Interestingly, PSZ exhibited abnormally larger variability in allocating memory resources across items and trials. Our findings challenged the classical "limited capacity" account in PSZ and showed that larger resource allocation variability was the major determinant of the VWM deficits in PSZ, which could only be detected by the VP framework.

Keywords: Schizophrenia, Visual working memory

Background

Working memory deficits have long been considered as a core cognitive impairment among the people with schizophrenia. Early research attributed these deficits to the reduced memory *capacity* in PSZ. Recent development of computational models of VWM has shown that other components besides the capacity, such as *precision*, also strongly mediate VWM performance (Ma, Husain, & Bays, 2014). However, few studies attempted to model the memory precision and the capacity in schizophrenia (Gold et al., 2010). They found that memory capacity rather than precision was the major factor contributing to the atypical behavior in PSZ.

Past years have seen the rapid progress in understanding the mechanistic nature of VWM. More elaborated computational models emerge and allow us to quantify the role of different memory components that alter behavior. Weiji Ma and his colleagues proposed a variable precision (VP) framework (van den Berg, Awh, & Ma, 2014; van den Berg, Shin, Chou, George, & Ma, 2012). This framework describes the full generative process where several VWM components (i.e., memory resource) jointly produce a behavioral choice. The key feature of this framework is to propose that the resource varies across stimuli and trials as such leading to variable memory precision. The VP framework has been shown as the state-of-the-art computational framework of VWM so far and the VP models outperformed other conventional models in a benchmark VWM dataset (van den Berg et al., 2014)

In the current study, we employed the VP framework to contrast the VWM process in both PSZ and HCS, aiming to examine in which aspect of VWM did the groups of PSZ and HCS significantly differ.

Methods

Experiment and stimuli. Performance of 60 PSZ and 61 demographically matched HCS was measured in a color delay-estimation task (Fig. 1) (Zhang & Luck, 2008). Subjects were asked to remember the colors of a set of squares, and after a short delay, to recall the color of a cued square by choosing its color on a color wheel. The set size (i.e., the number of squares in total) was either 1 or 3. Each set size included an experimental block of 80 trials and subjects completed two such blocks for two set size levels. The distance (in radian) in the color space between the reported color and the real color of the cued target was calculated as the response error in each trial.

The VP model. Although several variants of VP models exist, we used the standard VP model documented in van den Berg et al. (2012). We briefly summarize it as follows.

The VP model inherits the continuous resource theory of VWM and assumes that the mean memory resource ($\overline{J}$) assigned to individual items declines as the set size (N) increases (Bays, Catalao, & Husain, 2009):

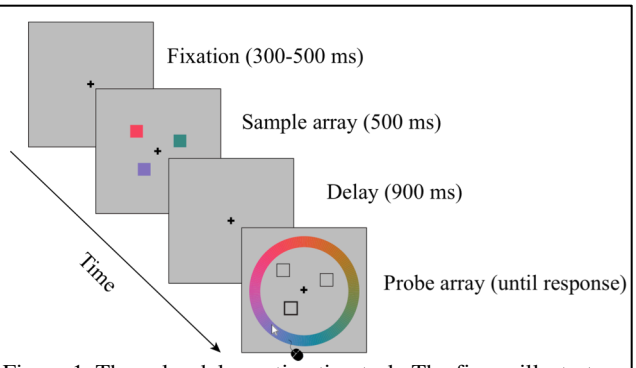

Figure 1. The color delay-estimation task. The figure illustrates an example trial (set size = 3). A trial begins with a fixation, followed by a sample array showing three (or one) colored squares for 500 ms. After a 900-ms delay period, subjects choose the remembered color of the cued item on the color wheel using a computer mouse.

$$\overline{J} = \overline{J_1} * N^{-a} \quad , \tag{1}$$

where $\overline{J_1}$ is the *initial resource* when only 1 item (N = 1) should be memorized and a is the *decay exponent* describing the rate of the declining trend. The key assumption here is that the memory resource J varies across items and trials. J follows a Gamma distribution with the mean $\overline{J}$ and the scale parameter τ:

$$J \sim Gamma(\overline{J}, \tau) \ , \tag{2}$$

Intuitively, a larger τ indicates memory resources are distributed across items or trials in a more heterogeneous manner, with some items in particular trials receiving larger amount of resource while others receiving very little. Here we denote τ as *resource allocation variability*. Note that a larger amount of memory resource produces a higher precision. Thus, we do not explicitly distinguish resource and precision here and denote both as *J*. Defined as fisher information (Ma, Beck, Latham, & Pouget, 2006), precision J can be linked to the variance of the von Mises distribution that generates the sensory measurement:

$$J = k\frac{I_1(\kappa)}{I_0(\kappa)}, \tag{3}$$

where I_0 and I_1 are modified Bessel functions of the first kind of order 0 and 1 respectively, with the concentration parameter κ. Equation (3) specifies a one-on-one mapping between precision J and the variance κ of the sensory measurement distribution. This mapping function can be rewritten as:

$$\kappa = \Phi(J), \tag{4}$$

where Φ is the mapping function. The probabilistic distribution of sensory measurement (m) given the input stimulus (s) can be written as:

$$p(m \mid s) = \frac{1}{2\pi I_0(\kappa)} e^{\kappa \cos(m-s)} \equiv VM(m; s, \kappa), \tag{5}$$

We further assume that the reported color ($\hat{s}$) by participants also follows a von Mises distribution:

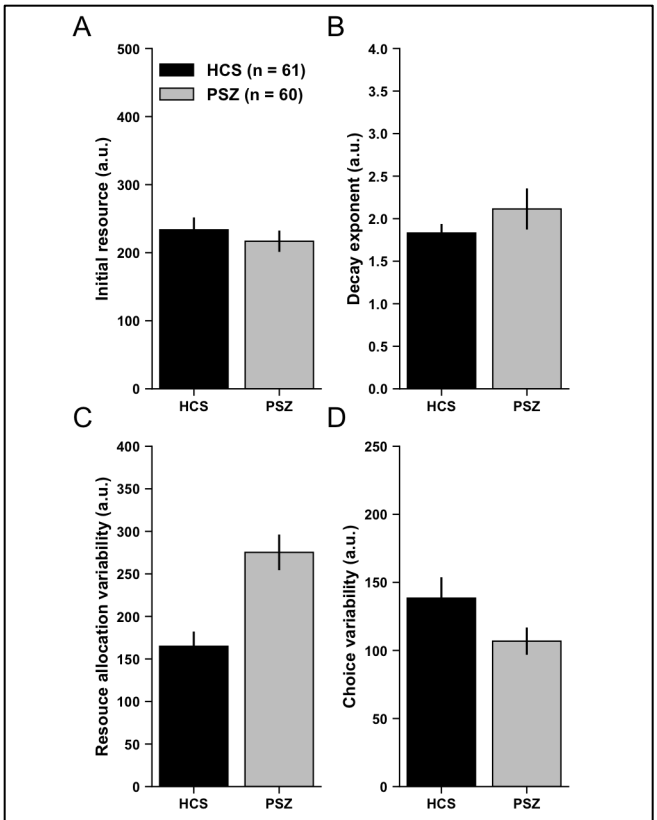

Figure 2. Fitted parameters of the VP model. No significant group differences were found in initial resource (A), decay exponent (B) and choice variability (D). PSZ showed larger resource allocation variability compared to HCS (C). All errorbars are SEM across subjects.

$$p(\hat{s} \mid m) = \frac{1}{2\pi I_0(\kappa_r)} e^{\kappa_r \cos(\hat{s}-m)} \equiv VM(\hat{s}; m, \kappa_r) \ , \tag{6}$$

where k_r represents the variability at the choice stage and we denote it as *choice variability*.

Taken together, this standard VP model has four free parameters: $\overline{J_1}$, a, τ and k_r

Results

We fit the VP model to estimate four components of VWM for all subjects. Our results suggest that the resource decaying function is comparable between PSZ and HCS (Fig. 2A, initial resource, t(119) = 0.689, p = 0.492, d = 0.125; Fig. 2B, decay exponent, t(119) = 1.065, p = 0.289, d = 0.194), indicating a similar trend of set-size-dependent decrease in the mean VWM precision. However, PSZ exhibited a larger variability in the trial-by-trial resource allocation (Fig. 2C, t(119) = 4.03, p = 9.87×10^{-5}, d = 0.733). These findings suggest that, although the two groups have the same amount of VWM resources on average at a certain level of set size, the ability to allocate resources in PSZ is more heterogeneous, with some items in particular trials receiving larger amounts and vice versa in other cases. Also, no group difference was found in the choice

variability (Fig. 2D, $t(119) = 1.7034$, $p = 0.091$, $d = 0.31$), excluding the possibility that the VWM deficits in PSZ are the consequences of noise in motor or decision-making processes. Note that heterogeneous resource allocation is detrimental for this task as the cued target is randomly chosen. A more optimal strategy is to equally distribute resources to face the unpredictable target.

Conclusion

Our study proposes a new explanation that the variability to allocate resource accounts for the atypical VWM performance of people with schizophrenia. This view contradicts with the conventional theory assuming the limited capacity and provides a prime for future studies aiming for improving diagnosis or rehabilitation for schizophrenia.

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