Journal of Cognitive Psychology

ISSN: 2044-5911 (Print) 2044-592X (Online) Journal homepage: http://www.tandfonline.com/loi/pecp21

The level of subjective visibility at different stages of memory processing

Zuzanna Skóra & Michał Wierzchoń

To cite this article: Zuzanna Skóra & Michał Wierzchoń (2016) The level of subjective visibility at different stages of memory processing, Journal of Cognitive Psychology, 28:8, 965-976, DOI: 10.1080/20445911.2016.1225745

To link to this article: http://dx.doi.org/10.1080/20445911.2016.1225745

JOURNAL OF COGNITIVE PSYCHOLOGY, 2016
VOL. 28, NO. 8, 965–976
http://dx.doi.org/10.1080/20445911.2016.1225745

Routledge
Taylor & Francis Group

The level of subjective visibility at different stages of memory processing

Zuzanna Skóra and Michał Wierzchoń

Consciousness Lab, Institute of Psychology, Jagiellonian University, Krakow, Poland

ABSTRACT
Recent research suggests that the content of iconic memory (IM) and fragile visual short-term memory could be associated with a similar level of conscious accessibility as working memory (WM). The results of our studies, in which we used a subjective visibility scale in a partial-report change detection paradigm, indicate that it is possible to distinguish separate stages of memory based on both discriminative accuracy and conscious accessibility. The highest scores were associated with IM and the lowest with WM, while somewhere in the middle there was fragile memory. Based on classical assumptions, WM accessibility should be greater than the other two types of memory; however, our study showed that this might not always be the case. We discuss the potential sources of this outcome, of which one may be the task construction, as we only tested items that were directly in the focus of attention.

ARTICLE HISTORY
Received 26 April 2016
Accepted 4 August 2016

KEYWORDS
Subjective visibility; iconic memory; working memory; fragile memory; partial-report change detection paradigm

Introduction

As described by the classical models, memory is not a unified system (see e.g. Atkinson & Shiffrin, 1971; Baddeley, 2012). It can be divided into the sensory register (e.g. iconic memory – IM), working memory (WM), and long-term memory (LTM). IM, which is the first stage of visual information processing, is probed best through Sperling's partial-report paradigm (1960). He presented, for a very short time, an array of letters arranged in rows. Through cuing one of the rows with an audio cue after the presented stimuli disappeared, Sperling discovered that more letters were recalled with this partial cue than without. Therefore, he demonstrated that there is probably more information held in IM than could be reported in a whole report paradigm in which no cue is utilised (Sperling, 1960).

Even though participants could recall only a portion of information stored in IM, they claimed that they "saw" the whole array of letters during the partial-report paradigm. Based on the presented data and on subjective reports of participants, there is currently a debate regarding the subjective accessibility of the content of different types of visual memory. Researchers agree that IM and visual WM (vWM) differ in terms of the subjective accessibility of their content, although they do not agree on how they differ (Block, 2011; Cohen & Dennett, 2011; Lamme, 2006). It is possible that the classical partial-report paradigm is not suitable for investigating the claimed differences. For example, the paradigm has classically been based on verbal material (letters) which could confound our investigations focused only on visual memory. With this in mind, we have used a modified version of this paradigm, namely, the partial-report change detection paradigm described below.

The empirical question of IM accessibility is strongly related to a much more important theoretical question on where consciousness arises in the memory system. Could it be at the early stage of information processing, or maybe at later stages? Classically, only WM (as opposed to IM and LTM) is viewed as a conscious stage of memory processing. Atkinson and Shiffrin (1971) assumed that the content of WM represented conscious thought, although they have also claimed, that "(…) Such a statement lies in the realm of phenomenology and, as stated, cannot be scientifically verified" (Atkinson & Shiffrin, 1971, p. 5). On the other hand, recent models associate awareness with earlier stages of information processing (see e.g. Lamme, 2006; Sandberg et al., 2013).

Here we propose coming back to this question and, through utilising subjective awareness

CONTACT Zuzanna Skóra zuzanna.skora@uj.edu.pl

measures, explore when and to what extent the information processed during the different stages of memory becomes accessible to consciousness.

Is WM content indeed accessible to consciousness?

Contrary to the classical approaches described above, recent studies question the direct link between WM and consciousness (Soto, Mäntylä, & Silvanto, 2011; Soto & Silvanto, 2014). In one of these studies, regarding vWM, Soto and colleagues presented an example of vWM operating on unconscious content. They compared accuracy in a discrimination task with subjective assessment of visibility, using the Perceptual Awareness Scale (PAS – Ramsøy & Overgaard, 2004). Even on trials where participants claimed no visibility (1 – "no experience"), vWM performance was above the chance discrimination accuracy. This was true over a 5-second delay period. The conclusion was that vWM and consciousness might be independent after all (Soto & Silvanto, 2014).

A considerable number of studies investigating the relation between WM and consciousness utilised a modified change detection paradigm to explore different stages of memory, specifically to assess the capacity and subjective accessibility of information (Lamme, 2006; Vandenbroucke et al., 2014). During the classical change detection task (Rensink, 2002), participants are presented with an array of objects or a visual scene (memory display) and, after a short interval with some kind of a disruption, a second display (test display) is presented in which a small change might have occurred. Participants have to detect whether a change occurred. The capacity denotes the number of items possibly held in memory. In order to control the focus of attention, Vandenbroucke, Sligte, and Lamme (2011) and Vandenbroucke et al. (2014) combined this task with Sperling's partial-report paradigm and called it a partial-report change detection paradigm. During their research, they proposed extracting a new stage in visual memory processing, called fragile visual short-term memory (FM). FM is claimed to be independent of attention and therefore qualitatively different from WM (Vandenbroucke et al., 2011). In a study by Sligte, Scholte, and Lamme (2008), FM was dissociated from IM because FM, in contrast to IM, did not appear to be erased by a light mask. The conclusion was that unlike like IM, FM was not based on the afterimage and could only be erased by the appearance of new items on the display (Sligte et al., 2008). Sligte and colleagues also claim that FM may represent "perception without immediate cognitive access", also referred to as "perceptual consciousness" by some (Block, 2011).

Memory capacity measured using a change detection task

Faced with the data presented above regarding the separation between WM and consciousness and the theoretical assumptions about consciousness associated with IM or FM, one would need to first separate these stages of memory based on objective processing limits (i.e. capacity).

With use of the change detection task, researchers were able to assess the number of items possibly held in vWM, which fluctuates between 2 and 7 items, depending on the complexity and type of the object. Combining a change detection task with a partial-report paradigm helped to assess the capacity of IM (e.g. Sligte et al., 2008). Through introducing a spatial cue during the interval in a change detection task, researchers assessed the capacity of IM for around 30 items (which were usually white rectangles on a black background – Sligte et al., 2008). By introducing the cue later than 300–500 ms, but earlier than 4 s after the offset of the memory display, the capacity still remained around twice the capacity of the vWM condition (i.e. with offset >4 s – see Sligte et al., 2008). Some researchers interpret this effect such that cuing may protect the items held in memory from interference from the test display (Makovski, Sussman, & Jiang, 2008), or that cuing leads to removing the uncued items and therefore freeing capacity (Souza, Rerko, & Oberauer, 2014). Other researchers suggest that there is an additional storage between IM and WM with a set of qualitatively different characteristics, namely, FM (Vandenbroucke et al., 2011) with a capacity of up to 15 elements.

We attempt to test whether these three memory stages could indeed be separated based not only on the capacity limits, but also on the accessibility of their content to conscious processing.

Conscious accessibility measured using a change detection task

To assess conscious processing in memory, Vandenbroucke et al. (2014) compared objective and subjective measures in a partial-report change detection paradigm for the three memory stages: IM, FM, and WM. The measure obtained through comparing task accuracy with subjective ratings is often called metacognitive sensitivity (the ability to discriminate correct judgments from incorrect – Fleming & Lau, 2014).[1]

What Vandenbroucke and colleagues found was that the IM and WM are associated with a similar level of metacognitive sensitivity, which is less pronounced than the metacognitive sensitivity for FM. In their second study, in which participants performed a discrimination task instead of change detection, the three memory types were associated with the same level of metacognitive sensitivity. How Vandenbroucke and colleagues explain this effect is that the FM's high capacity is based on conscious information processing (2014). The results of this study contradict the classical view on memory, which states that only WM is accessible to consciousness.

Here, we propose that this surprising result might have its origin in the inappropriate subjective scale usage. This is because Vandenbroucke and colleagues used Confidence Rating (CR), which is a measure of metacognitive judgment of knowledge (i.e. judgment of the quality of the classification process but not the subjective visibility, see Overgaard & Sandberg, 2012).

Our study

The differences in capacity between the three aforementioned memory stages seem to be well described. What remains unresolved is the question of the differences between the memory stages regarding the conscious accessibility of processed information. So far, there is a discrepancy between classical theories which postulate a difference between WM and IM, and recent experiments which suggest that there is either an opposite difference (e.g. unconscious WM – Soto et al., 2011), or no difference at all (Vandenbroucke et al., 2014).

Our aim is to replicate the effect found in the paper by Vandenbroucke et al. (2014) which suggests that the three memory types do not differ in terms of conscious accessibility of their content. One of the major changes we made was administering a more appropriate subjective scale of awareness; namely PAS, which is a measure of subjective visibility, not a judgment of knowledge (Ramsøy & Overgaard, 2004). The experiments presented in this paper combine the partial-report change detection paradigm with the subjective visibility measure for the three types of memory: IM, FM, and WM

Experiment 1

The first experiment aims to investigate the accessibility of information under FM and WM conditions. We used the partial-report change detection paradigm, during which participants were required to first memorise the displayed items (memory display) and then perform a change detection task (test display). We employed two conditions: either the cue appeared before the test display (FM), or after a short presentation of the test display (WM). We further applied the PAS to evaluate conscious access to the content of memory.

Method

Participants

Twenty students from Jagiellonian University (7 males and 13 females with the mean age of 24.3, SD = 2.39) with normal or corrected-to-normal vision took part in the first experiment. Two participants were excluded from further analysis due to their apparently random performance in the WM condition (accuracy around 50%). Participants read and signed an informed consent form prior to the study and were debriefed regarding the purpose of the experiment at the end. There was no financial compensation.

Equipment and stimuli

The experiment was created and run on PsychoPy v.1.79.01 Software®. The stimuli were displayed on a 16.4 in, generic PnP monitor with a refresh rate of 60 Hz. Participants were tested individually while seated about 50 cm from the monitor (the viewing distance was unconstrained). The total viewing angle of the display was approximately 40.1° × 23.2°.

The stimulus was placed on a black background and consisted of eight white rectangles (each 3.12° × 0.78° in size) in horizontal, vertical or oblique (45° or 135°) orientations. The fixation point was a red cross (height of 0.1°, Arial font)

[1]Usually this is associated with confidence ratings; in our study, we obtain this measure by comparing task accuracy with PAS ratings.

placed at the centre of the display. All the rectangles were arranged in an imaginary circle around the fixation point. The cue was a white six-pixel-thick line with one end pointed at the fixation point and the other at one of the rectangles.

Trial design

The experiment was designed for within-subject manipulation. Each trial of the primary task consisted of two displays. The first was a memory display during which participants were required to memorise the orientation of a set of eight rectangles. There was a 50% chance that one of the rectangles would change orientation between the memory and the test display. The rectangle that could change orientation was cued during the interval between the two displays (FM condition) or after the test display presentation (WM condition). During the test display, participants were required to answer whether there was a change in the cued rectangle's orientation by pressing one of the arrow keys on the keyboard: the right arrow was pressed for "change" and the left arrow for "no change".

The memory display began with a 1000 ms fixation point. Memory stimuli subsequently appeared for 250 ms. After the offset of the memory stimuli, only the fixation point remained on the screen. The flow of events during each trial is presented in Figure 1.

The time duration between memory display and testing display in each trial was manipulated between groups. In the FM condition (Vandenbroucke et al., 2014), the inter-stimulus-interval (ISI) lasted for 2000 ms. and the length of the ISI in the WM condition was 900 ms. The key difference between the conditions was the cue presentation, which could be either before the test display, or a moment after. During the FM condition, the cue appeared 900 ms after the offset of the memory display. In the WM condition, the cue was provided 1000 ms after the offset of the memory display and, more importantly, it appeared 100 ms after the test display onset. In both conditions, the duration of the cue was 100 ms. The test display remained present until the response. The experimental conditions, that is, timing and stimuli, were mostly based on Vandenbroucke et al. (2014), with the exception of the number of rectangles presented in each trial (which we kept constant) and the scale (see Figure 1 for the overview of the procedure).

At the end of each trial, after the change detection response, participants were required to provide a subjective assessment of target visibility. The PAS was provided with a short description of each point: 1 – no experience; 2 – weak experience; 3 – almost clear experience; and 4 – absolutely clear experience (Ramsøy & Overgaard, 2004). Participants completed 15 practice trials at the beginning of the experiment that were excluded from further analysis. The experiment consisted of 500 randomly intermixed trials (250 trials per each condition).

Data analysis

The analysis was performed using Matlab r2015a Software, MathWorks® (Massachusetts, USA) utilising the functions to calculate change detection sensitivity (d′) and metacognitive sensitivity (meta-d′) provided by Maniscalco (2014) and Maniscalco and Lau (2012). We chose the function that uses maximum likelihood estimation (*fit_meta_d_MLE*). We also calculated the deviation from the diagonal, called Area Under the Curve (AUC), which provides a bias-free measure of metacognitive sensitivity. To calculate AUC we used the function provided by

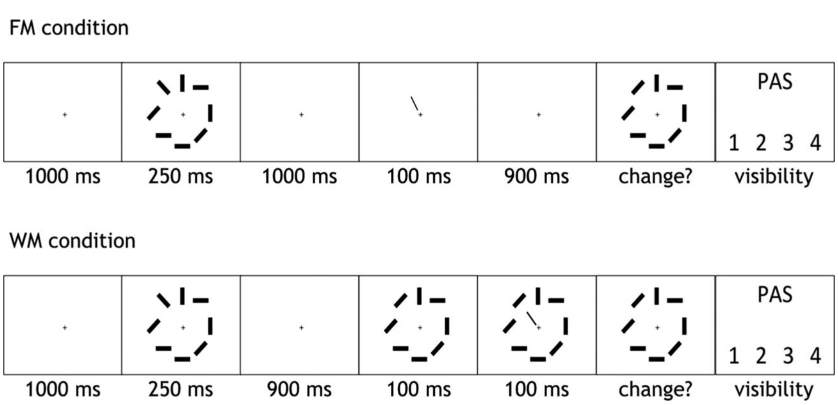

Figure 1. Flow of events during the FM (top) and the WM (bottom) conditions.

Lau (2014). The data for the analysis included the correct and incorrect responses along with the subjective visibility assessment in a trial-by-trial format. The analysis presented below, comparing the measures mentioned above in a between-subject design, was run as a Bayesian paired samples *t*-test. The Cauchy prior width was fixed at a default level of 0.707, as suggested in JASP®, the free open-source statistics package (Love et al., 2015) in which the analysis was run.

Results and discussion

To objectively evaluate performance, the d′ sensitivity was calculated for each participant. The hypotheses tested was that the d′ for FM would be higher than for the WM condition. The average d′ for the FM condition was $M = 1.86$ (SD = .70) and for the WM condition was $M = 1.01$ (SD = .46). This data were more likely to be found under the alternative hypothesis, as $BF_{10} > 1000$.

We calculated the mean PAS values for each participant to check whether they differed between conditions. For the FM condition, $M = 3.09$ (SD = .38), and for the WM condition, $M = 2.67$ (SD = .42). The Bayes Factor for the alternative hypothesis reached the level of $BF_{10} > 1000$, indicating that the data were more likely to occur under the alternative hypothesis.

To assess the level of metacognitive sensitivity, we analysed the type II Receiver Operating Characteristic (ROC) curve. The mean AUC for FM reached $M = .77$ (SD = .08) and for WM, $M = .67$ (SD = .07). The data were more probable under the alternative hypothesis, as $BF_{10} > 1000$ (see Figure 4. for the Receiver Operating Curves for Experiments 1 and 2).

We also calculated a measure of metacognitive sensitivity, called the meta-d′ (Maniscalco & Lau, 2012). The meta-d′ in the FM condition reached $M = 1.81$ (SD = .59) and in the WM condition, $M = .98$ (SD = .49). The data were more probable under the alternative hypothesis, as $BF_{10} > 1000$.

To take into account the variability of d′ across the conditions when assessing metacognitive accuracy, we calculated the meta-d′/d′ value (called the metacognitive efficiency – Fleming & Lau, 2014) for each condition for every subject. For the FM condition, $M = 1.03$ (SD = .30) and for the WM condition, $M = 1.00$ (SD = .33). The data were more probable under the null hypothesis, as $BF_{01} = 3.84$. The ratio of around 1 shows that all information available for the discrimination task was also available for the visibility judgment (see Figure 2 for a bar chart depicting the values of d′, meta-d′, and meta-d′/d′).

We observed differences in the objective accuracy between FM and WM that were followed by differences in metacognitive sensitivity. In both cases, FM seemed superior to WM. These results suggest that WM and FM represent different levels of metacognitive sensitivity. After correcting for the differences in accuracy, it appeared that both types of memory have an equal level of metacognitive efficiency (i.e. the meta-d′/d′). The utility of this measure will be discussed later in the text. To investigate whether there are any differences between FM and the IM, we conducted a second experiment.

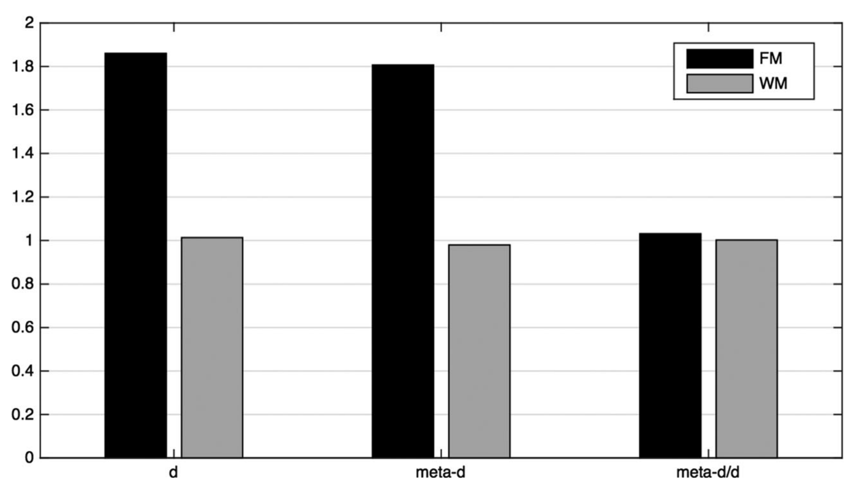

Figure 2. Results from Experiment 1. The separate bars represent the mean sensitivity (d′), the metacognitive sensitivity (meta-d′), and the metacognitive efficiency (meta-d′/d′) as a function of condition.

Experiment 2

The second experiment's aim was to investigate the accessibility of information under the FM and IM conditions. Again, we used the partial-report change detection paradigm, for which we employed two conditions. The conditions differed in cue presentation timing. As previously, we applied the PAS to evaluate conscious access to the content of memory.

Method

Participants

Nineteen students from Jagiellonian University (4 males and 15 females with the mean age of 21.7, SD = 2.63) with normal or corrected-to-normal vision took part in the second experiment. Two participants were excluded from further analysis due to their random performance in the FM condition (accuracy around 50%). Participants read and signed an informed consent form prior to the study and were debriefed regarding the purpose of the experiment at the end. There was no financial compensation.

Equipment and stimuli

The equipment and the stimuli were the same as in the first experiment.

Trial design

The procedure was analogical to the one from the first experiment except that the WM condition was replaced with the IM condition and compared with the FM condition (Vandenbroucke et al., 2014). The ISI duration in the IM condition was 1050 ms and the cue appeared 50 ms after the offset of the memory display (see Figure 1). Participants were also required to provide an answer regarding the visibility of the stimulus after deciding whether a change had occurred (see Figure 3. for the overview of the procedure).

Participants completed 15 practice trials at the beginning of the experiment that were excluded from further analysis. The experiment consisted of 500 randomly intermixed trials (250 trials per each condition).

Data analysis

The data were analysed in the same manner as in the first experiment.

Results and discussion

In order to evaluate performance objectively, we calculated d′ sensitivity for each participant. The hypotheses tested was that d′ for FM would be lower than for the IM condition. The mean d′ for the FM condition was $M = 1.67$ (SD = .69) and for the IM condition, $M = 2.23$ (SD = .82). The data were more probable under the alternative hypothesis, as $BF_{10} > 1000$.

The mean PAS values calculated for each participant were $M = 2.97$ (SD = .45) for the FM condition and $M = 3.29$ (SD = .45) for the IM condition. The data were more probable under the alternative hypothesis, as $BF_{10} > 1000$.

The mean AUC for FM reached $M = .75$ (SD = .08) and for IM, $M = .81$ (SD = .08). The data were more probable under the alternative hypothesis, as $BF_{10} > 100$ (see Figure 4 for the Receiver Operating Curves for Experiment 1 and 2).

The meta-d′ in the FM condition reached $M = 1.61$ (SD = .60) and in the IM condition, $M = 2.10$ (SD = 1.02). The data were more probable under the alternative hypothesis, as $BF_{10} = 6.14$.

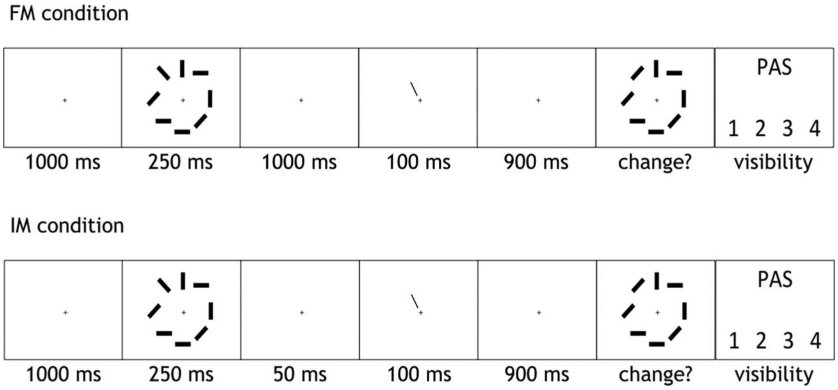

Figure 3. Flow of events during the FM (top) and the IM (bottom) conditions.

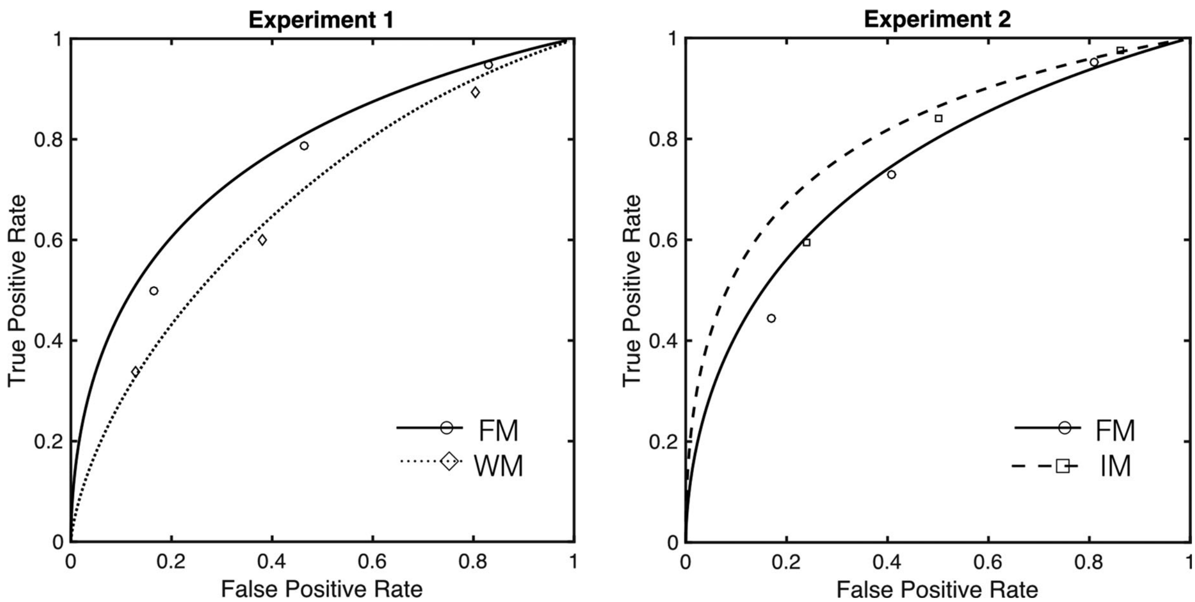

Figure 4. Type II receiver operating curves for Experiment 1 and 2.

The meta-d′/d′ value for the FM condition was $M = 1.02$ (SD = .29) and for the IM condition was $M = .96$ (SD = .31). The data were more probable under the null hypothesis, as $BF_{01} = 3.29$ (see Figure 5 for a bar chart depicting the values of d′, meta-d′, and meta-d′/d′).

In the second experiment, we observed differences in the objective accuracy between IM and FM that were followed by differences in metacognitive sensitivity. In both cases, IM seemed superior to FM. These results would suggest that IM and FM represent different levels of metacognitive sensitivity. After correcting for the differences in task accuracy, it again appeared that both types of memory have an equal level of metacognitive efficiency. Correcting the metacognitive sensitivity measure for the differences in the objective performance may yield different results than keeping the objective accuracy at a similar level in all conditions, especially when we probe participants' subjective visibility on a trial-by-trial basis. Assuming the differences in objective accuracy influence metacognitive sensitivity, these two approaches may lead to different results. Therefore, we conducted another experiment, in which

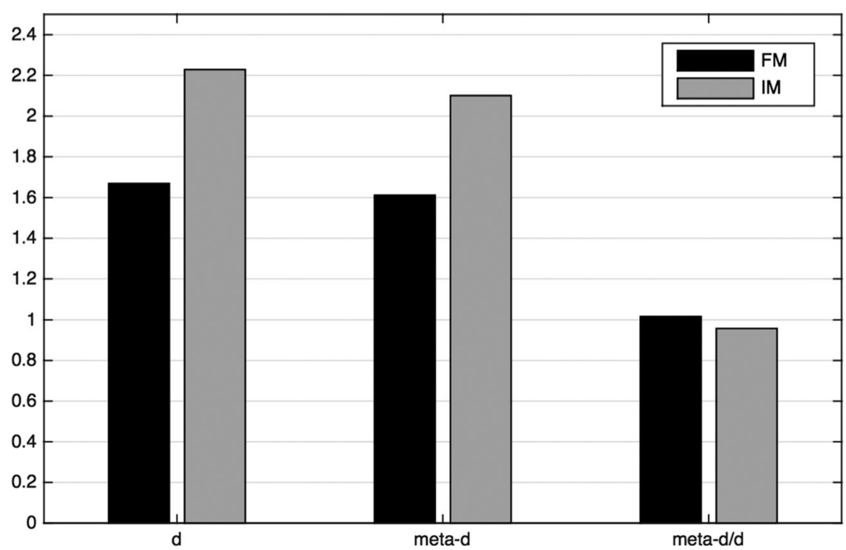

Figure 5. Results from Experiment 2. The separate bars represent the mean sensitivity (d′), the metacognitive sensitivity (meta-d′), and the metacognitive efficiency (meta-d′/d′) as a function of condition.

we introduced a staircase method to keep the performance at a similar level throughout the experiment. Additionally, we performed the experiment in a within-subject design.

Experiment 3

The third experiment's aim was to investigate the accessibility of information under FM, IM, and WM conditions in a within-subject design. We used a staircase procedure to keep the level of task accuracy similar between the conditions. Again, we used the partial-report change detection paradigm, for which we employed the three conditions. As previously, we applied the PAS to evaluate conscious access to the content of memory

Method

Participants

Nineteen students from Jagiellonian University (6 males and 13 females with mean age, $M = 20.11$, $SD = 1.33$) with normal or corrected-to-normal vision took part in the third experiment. One of the participants was excluded from further analysis due to inappropriate use of the response keys. Participants read and signed an informed consent form prior to the study and were debriefed regarding the purpose of the experiment at the end. As compensation, participants received course credits.

Equipment and stimuli

The experiment was programmed in Matlab r2015a Software, MathWorks® (Massachusetts, USA) using the Psychophysics Toolbox extension (Brainard, 1997; Pelli, 1997; Kleiner, Brainard, & Pelli, 2007). Participants were tested in groups and each participant was seated in an individual semi-booth, approximately 60 cm from the screen (the viewing distance was unconstrained). The stimuli were the same as in the two previous experiments. The only change concerned the number of white bars, which varied because of the staircase procedure.

Trial design

The procedure was analogical to the one from the first experiment except that all the conditions (IM, FM, and WM) were tested within-subject in separate blocks. We used the two-up one-down staircase procedure (García-Pérez, 1998). One bar was added to the memory display after two consecutive correct responses, and one bar was removed after one incorrect response. This type of staircase usually results in around 70% discriminative accuracy.

Participants completed 15 practice trials at the beginning of each block that were excluded from further analysis. The experiment consisted of 360 trials (120 trials per condition).

Data analysis

The data were analysed in the same manner as in the first experiment, except that a Bayesian Repeated Measures ANOVA was added to compare the three within-subject conditions.

Results and discussion

In order to evaluate performance objectively, we calculated the d′ sensitivity for each participant. The mean d′ for the FM condition was $M = 1.41$ ($SD = .41$); for the IM condition, $M = 2.20$ ($SD = .63$); and for the WM condition, $M = 1.07$ ($SD = .29$). The data were more probable under the alternative hypothesis, as $BF_{10} > 1000$. The *post hoc* analysis revealed that when comparing the FM and IM conditions, the alternative hypothesis was more likely, $BF_{10} > 100$; similarly when comparing the WM and IM conditions, $BF_{10} > 1000$; and FM with WM, $BF_{10} = 16.26$.

The mean PAS values calculated for each participant were as follows: for the FM condition, $M = 2.75$ ($SD = .43$); for the IM condition, $M = 3.15$ ($SD = .56$); and for the WM condition, $M = 2.80$ ($SD = .55$). The alternative hypothesis was more likely to be true, as $BF_{10} = 41.33$. The *post hoc* analysis, using a paired samples *t*-test, revealed that there was a difference between the FM and IM conditions, as $BF_{10} = 39.48$, and between the WM and IM conditions, as $BF_{10} = 7.28$. The FM and WM conditions did not differ, as $BF_{01} = 3.60$.

The mean AUC for FM reached the level of $M = .72$ ($SD = .05$); for IM, $M = .81$ ($SD = .07$); and for the WM, $M = .67$ ($SD = .04$). The observed data were more probable under the alternative hypothesis, as $BF_{10} > 1000$. *Post hoc* tests showed that the alternative hypothesis was more likely when comparing the FM and IM conditions, as $BF_{10} > 100$; the WM and IM, $BF_{10} > 1000$; and the FM with WM, $BF_{10} = 65.51$ (see Figure 6 for the receiver operating curves for Experiment 3).

The meta-d′ in the FM condition reached the level of $M = 1.54$ ($SD = .72$); in the IM condition, $M = 2.23$ ($SD = 1.23$); and in the WM condition, $M = 0.78$ ($SD = .49$). The alternative hypothesis was more likely to be true, as $BF_{10} > 1000$. The *post hoc* test

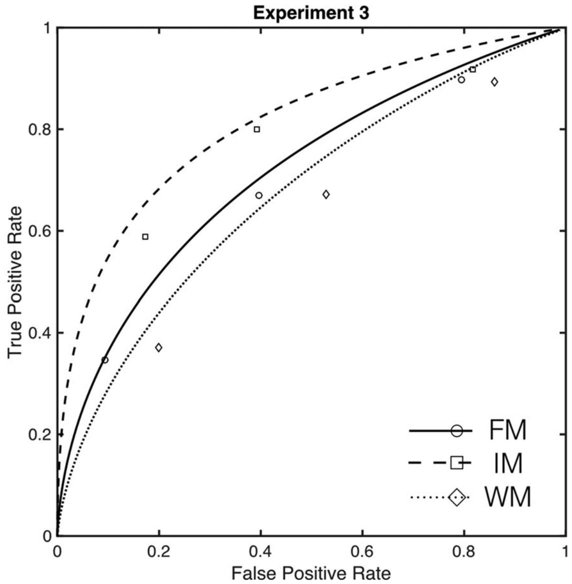

Figure 6. Type II receiver operating curves for Experiment 3.

for the difference between FM and IM revealed only an anecdotal level of evidence in favour of the alternative hypothesis, $BF_{10} = 1.65$. The difference between WM and IM was highly probable, as $BF_{10} > 100$, as was the difference between the FM and WM conditions, as $BF_{10} = 48.78$.

The meta-d′/d′ value for the FM condition, $M = 1.08$ (SD = .39); for the IM condition, $M = 1.03$ (SD = .43); and for the WM condition, $M = 0.74$ (SD = .49). There was only anecdotal evidence supporting the alternative hypothesis, as $BF_{10} = 2.31$. When the meta-d′/d′ was compared between the FM and IM conditions, the strength of evidence for the null hypothesis was moderate, as $BF_{01} = 3.85$. The strength of evidence for the difference between the WM and IM conditions was only anecdotal, $BF_{10} = 1.68$, as well as for the difference between the FM and WM, as $BF_{10} = 1.86$ (see Figure 7 for a bar chart depicting the values of d′, meta-d′, and meta-d′/d′).

In the third experiment, we observed differences in objective accuracy between all the conditions that were followed by differences in metacognitive sensitivity. As in the two previous experiments, in both cases IM seemed superior to FM and WM, and FM also seemed superior to WM. These results suggest that the three stages of memory do indeed represent different levels of metacognitive sensitivity. The safest conclusion we can draw from the analysis regarding the meta-d′/d′ index is that there is probably no difference in metacognitive efficiency between the FM and IM conditions. In addition, we observed that WM might be associated with lower metacognitive efficiency than both FM and IM, although the evidence is only anecdotal.

General discussion

The three memory stages investigated in our studies (i.e. IM, FM, and WM) seem to differ in the level of objective discrimination accuracy (i.e. capacity). The highest accuracy (d′) was associated with IM, then FM, and the lowest, with WM. We also observed differences in metacognitive sensitivity (AUC and meta-d′) that mirrored the differences in task

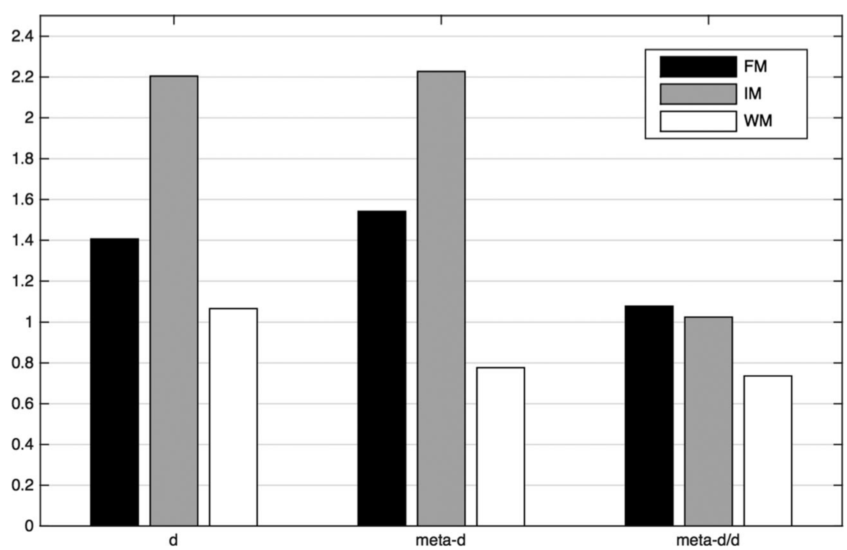

Figure 7. Results from Experiment 3. The separate bars represent the mean sensitivity (d′), the metacognitive sensitivity (meta-d′), and the metacognitive efficiency (meta-d′/d′) as a function of condition.

accuracy. After correcting for the differences in the task performance (meta-d′/d′), the conditions seem to represent the same level of metacognitive efficiency.

As we would expect, the observed task accuracy results are based on classical research focused on the capacity of WM and IM (Sperling, 1960) and those investigating FM, the additional stage in memory processing (Sligte et al., 2008; Vandenbroucke, Sligte, Barrett, et al., 2014; Vandenbroucke, Sligte, & Lamme, 2011). As predicted by the classical models, the capacity of IM seems to be much larger than the capacity of WM, with FM in the middle. The FM results are systematically different, which confirms the existence of the separate type of memory system proposed by Vandenbroucke et al. (2011). However, the results supporting the existence of FM could be alternatively interpreted as the retro-cue effect (e.g. Makovski et al., 2008). The retro-cue effect denotes the accuracy improvement after introducing a cue during the interval to inform participants which item is going to be tested (Makovski et al., 2008; Souza et al., 2014). It thus seems that one should analyse the differences in the accessibility of memory content to justify further the qualitative distinction between the aforementioned memory subsystems.

A similar pattern of results was found when subjective accessibility is taken into account (measured with the AUC, which, opposite to the meta-d′ measure does not have the ideal observer assumption – Maniscalco & Lau, 2012). We found that IM was associated with the highest level of subjective accessibility, WM with the lowest, and FM again somewhere in the middle. These results do not go hand in hand with the data obtained by Vandenbroucke et al. (2014), in which FM represented the highest level of metacognitive sensitivity, and IM and WM were slightly worse. This is important, as Vandenbroucke and colleagues interpret this effect as evidence for equal accessibility of items processed by IM and WM, which is not confirmed by our data. Importantly, our data are also not consistent with the classical models of WM, suggesting that WM accessibility should be better than both FM and IM (Atkinson & Shiffrin, 1971; Baddeley, 2012).

One of the explanations regarding the differences between our study and the study by Vandenbroucke et al. (2014) is associated with the scale utilised to measure the subjective visibility of the stimulus. Instead of using the same CR scale that taps into judgment knowledge as Vandenbroucke et al. (2014), we decided to administer the PAS as it is claimed to be more suitable for perceptual tasks and may capture visibility more directly (Overgaard & Sandberg, 2012). This would explain why we obtained different results than Vandenbroucke and colleagues, but not why WM content was found to be least accessible (which is contrary to the assumptions of most of the aforementioned WM models).

The other possible explanation relates to the very assumption of different memory subsystems being engaged in the task conditions. Note that in all of the conditions, we only asked about the subjective accessibility of the currently cued stimulus. Thus, even in the IM condition, we did not test the accessibility of pure IM, but rather the accessibility of the element processed in IM for which the processing was further amplified by cuing attention to that element (e.g. Thibault, van den Berg, Cavanagh, & Sergent, 2016). This seems to be supported by the meta-d′/d′ index analysis, according to whose results metacognitive efficiency is equal for the three aforementioned stages of memory. Although it would seem that this supports claims put forward by Vandenbroucke et al. (2014), we argue that it does not. Assuming the interpretation mentioned above, using the partial-report change detection procedure in the current form can only inform us about the accessibility of the cued item, which may differ from the accessibility of the other items.

This interpretation reflects the classical way of studying conscious accessibility, in which consciousness was strongly linked to attention. One example is Baars' Global Workspace theory (see e.g. Baars & Franklin, 2003), which assumes that consciousness is associated with global distribution of information in the brain and that all the components of WM that become activated are conscious (e.g. rehearsal or visuospatial operations). The close link between consciousness and attention is postulated by some of the most prominent models of awareness (Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006). However, many other scientists disagree (Bronfman, Brezis, Jacobson, & Usher, 2014; Lamme, 2006) and provide evidence in favour of the disunity of these two phenomena or draw attention to the conscious processes outside of the focus of attention. Solving this problem could help answer the question whether the content of WM must necessarily be conscious and what the relation is between WM and attention. It will also help to determine to what extent IM, FM, and WM are consciously accessible. For now, there is a discrepancy between the classical theories of memory and new empirical evidence (Atkinson & Shiffrin, 1971; Baars & Franklin, 2003; Soto et al., 2011; Vandenbroucke et al., 2014).

While being reviewed in the context of studies investigating differences between WM, IM and FM, the data we acquired seem puzzling, though when seen in the light of current studies engaged in exploring the function of WM, the interpretation begins to be quite straightforward. A model introduced by Nelson Cowan and further developed by Klaus Oberauer (Cowan, 1988; Oberauer, 2009) describes memory as a functionally specialised (but structurally unified) system, with attention at the base of the functional distinction. This model accounts for the possibility of WM operating on unconscious information. Cowan unified LTM with WM, assuming WM to be an activated part of LTM. WM, according to this model, can be decomposed into the region of direct access and the focus of attention. These two stages of WM differ in capacity, with only one element being held in the focus of attention, though the attention could fluctuate between four elements. The model also assumes that only the element in the focus of attention is processed consciously (Oberauer, 2009). This again seems to be consistent with the proposed interpretation of our results; namely, that the cue induces attentional amplification but not differences in conscious access between IM, FM, and WM. For this purpose, one should instead test the accessibility of the information that did not reach the focus of attention due to the cue presentation.

To sum up, the extraordinary results acquired by Vandenbroucke et al. (2014) suggested that the IM and FM might be associated with conscious processing. This postulation was based on the observation of the similar accessibility of the content in WM and IM (Vandenbroucke et al., 2014). Our results did not support this interpretation as we observed a difference in WM and IM capacity and accessibility (however, see the results of meta-d′/d′ index). A question remains whether the partial-report change detection paradigm in its current form enables items outside of the focus of attention to be studied in order to tap into the IM or FM processing. The next logical step would be to investigate the subjective visibility outside of the focus of attention (see Bronfman et al., 2014). It also seems important to choose an appropriate method for assessing the subjective accessibility of the memory content that is based purely on the experience of stimulus and is not associated with any judgment regarding the efficiency of cognitive processes.

Disclosure statement

No potential conflict of interest was reported by the authors.

The underlying research materials for this article can be accessed at: https://osf.io/fdcgk/

Funding

This work was supported by the National Science Centre, Poland [Grant Harmonia number 2014/14/M/HS6/00911] awarded to MW.

ORCiD

Zuzanna Skóra http://orcid.org/0000-0001-6018-8031
Michał Wierzchoń http://orcid.org/0000-0002-7347-2696

References

Atkinson, R. C., & Shiffrin, R. M. (1971). *The control processes of short-term memory*. Technical Report. Stanford, CA: Institute for Mathematical Studies in the Social Sciences.

Baars, B. J., & Franklin, S. (2003). How conscious experience and working memory interact. *Trends in Cognitive Sciences*, *7*(4), 166–172. doi:10.1016/S1364-6613(03)00056-1

Baddeley, A. (2012). Working memory: Theories, models, and controversies. *Annual Review of Psychology*, *63*, 1–29.

Block, N. (2011). Perceptual consciousness overflows cognitive access. *Trends in Cognitive Sciences*, *15*(12), 567–575. doi:10.1016/j.tics.2011.11.001

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision*, *10*, 433–436.

Bronfman, Z. Z., Brezis, N., Jacobson, H., & Usher, M. (2014). We see more than we can report: "Cost free" color phenomenality outside focal attention. *Psychological Science*, *1*, 1–10. doi:10.1177/0956797614532656

Cohen, M. A., & Dennett, D. C. (2011). Consciousness cannot be separated from function. *Trends in Cognitive Sciences*, *15*(8), 358–364. doi:10.1016/j.tics.2011.06.008

Cowan, N. (1988). Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information-processing system. *Psychological Bulletin*, *104*(2), 163–191.

Dehaene, S., Changeux, J. P., Naccache, L., Sackur, J., & Sergent, C. (2006). Conscious, preconscious, and subliminal processing: A testable taxonomy. *Trends in Cognitive Sciences*, *10*(5), 204–211. doi:10.1016/j.tics.2006.03.007

Fleming, S. M., & Lau, H. C. (2014). How to measure metacognition. *Frontiers in Human Neuroscience*, *8*(443), 1–9. doi:10.3389/fnhum.2014.00443

García-Pérez, M. A. (1998). Forced-choice staircases with fixed step sizes: Asymptotic and small-sample properties. *Vision Research*, *38*(12), 1861–1881. doi:10.1016/S0042-6989(97)00340-4

Kleiner, M., Brainard, D., & Pelli, D. (2007). *What's new in psychtoolbox-3*? Perception 36 ECVP Abstract Supplement.

Lamme, V. A. F. (2006). Towards a true neural stance on consciousness. *Trends in Cognitive Sciences*, *10*(11), 494–501. doi:10.1016/j.tics.2006.09.001

Lau, B. (2014). *Matlab code for the area under the receiver operating curve (AUC) and confidence intervals* [*code*]. Retrieved from https://github.com/brian-lau/MatlabAUC

Love, J., Selker, R., Marsman, M., Jamil, T., Dropmann, D., Verhagen, A. J., & Wagenmakers, E.-J. (2015). *JASP* (Version 0.7) [Computer software]. Amsterdam, The Netherlands: JASP Project.

Makovski, T., Sussman, R., & Jiang, Y. V. (2008). Orienting attention in visual working memory reduces interference from memory probes. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *34*(2), 369–380. doi:10.1037/0278-7393.34.2.369

Maniscalco, B. (2014). *Type 2 signal detection theory analysis using meta-d'* [*code*]. Retrieved from http://www.columbia.edu/~bsm2105/type2sdt/

Maniscalco, B., & Lau, H. (2012). A signal detection theoretic approach for estimating metacognitive sensitivity from confidence ratings. *Consciousness and Cognition*, *21*(1), 422–430. doi:10.1016/j.concog.2011.09.021

Oberauer, K. (2009). Design for a working memory. *Psychology of Learning and Motivation*, *51*, 45–100. doi:10.1016/S0079-7421(09)51002-X

Overgaard, M., & Sandberg, K. (2012). Kinds of access: Different methods for report reveal different kinds of metacognitive access. 1287–1296. doi:10.1098/rstb.2011.0425

Pelli, D. G. (1997). The videotoolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*, *10*, 437–442.

Ramsøy, T. Z., & Overgaard, M. (2004). Introspection and subliminal perception. *Phenomenology and the Cognitive Sciences*, *3*(1), 1–23. doi:10.1023/B:PHEN.0000041900.30172.e8

Rensink, R. a. (2002). Change detection. *Annual Review of Psychology*, *53*, 245–277. doi:10.1146/annurev.psych.53.100901.135125

Sandberg, K., Bahrami, B., Kanai, R., Barnes, G. R., Overgaard, M., & Rees, G. (2013). Early visual responses predict conscious face perception within and between subjects during binocular rivalry. *Journal of Cognitive Neuroscience*, *25*(6), 969–985.

Sligte, I. G., Scholte, H. S., & Lamme, V. A. F. (2008). Are there multiple visual short-term memory stores? *Plos One*, *3*(2), e1699. doi:10.1371/journal.pone.0001699

Soto, D., Mäntylä, T., & Silvanto, J. (2011). Working memory without consciousness. *Current Biology*, *21*(22), R912–R913. doi:10.1016/j.cub.2011.09.049

Soto, D., & Silvanto, J. (2014). Reappraising the relationship between working memory and conscious awareness. *Trends in Cognitive Sciences*, *18*(10), 520–525. doi:10.1016/j.tics.2014.06.005

Souza, A. S., Rerko, L., & Oberauer, K. (2014). Unloading and reloading working memory: Attending to one item frees capacity. *Journal of Experimental Psychology: Human Perception and Performance*, *40*(3), 1237–1256.

Sperling, G. (1960). The information available in brief visual presentations. Doi:10.1037/h0093759

Thibault, L., van den Berg, R., Cavanagh, P., & Sergent, C. (2016). Retrospective attention gates discrete conscious access to past sensory stimuli. *PloS One*, *11*(2), e0148504. doi:10.1371/journal.pone.0148504

Vandenbroucke, A. R. E., Sligte, I. G., Barrett, A. B., Seth, A. K., Fahrenfort, J. J., & Lamme, V. A. F. (2014). Accurate metacognition for visual sensory memory representations. *Psychological Science*, *25*(4), 861–873. doi:10.1177/0956797613516146

Vandenbroucke, A. R. E., Sligte, I. G., & Lamme, V. A. F. (2011). Manipulations of attention dissociate fragile visual short-term memory from visual working memory. *Neuropsychologia*, *49*(6), 1559–1568. doi:10.1016/j.neuropsychologia.2010.12.044