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9   **Current directions in visual working memory research: an introduction and emerging insights**

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1   **Abstract**

2   Visual working memory (VWM) is a core construct in the cognitive (neuro-)sciences, assumed to

3   serve as a hub for information exchange and thus supporting a multitude of cognitive functions related to

4   processing visual information. Here, we give an introduction into key terms and paradigms and an

5   overview of ongoing debates in the field, to which the articles collected in this Special Issue on "Current

6   Directions in Visual Working Memory Research" contribute. Our aim is to extract, from this overview,

7   some 'emerging' theoretical insights concerning questions such as the optimal way to examine VWM,

8   which types of mental representations contribute to performance on VMW tasks, and how VWM keeps

9   features from the same object together and apart from features of concurrently maintained objects (the

10   binding problem).

11   *Keywords:* visual cognition, working memory, attention, binding, interference

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1   Current directions in visual working memory research: an introduction and emerging insights

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3   Visual working memory (VWM) – the mental workspace for the temporary storage and manipulation

4   of visual information – is a central cognitive faculty at the interface between visual perception and goal-

5   directed action. It is pivotal for making sense of the constantly changing stream of information arriving

6   through the visual system: Objects move, our eyes move, our body moves, even the whole world may

7   appear to move (such as on a merry-go-round). To keep track of agents and things in this rapid flow, it is

8   crucial to maintain and match representations of relevant visual objects across all these changes (Aagten-

9   Murphy & Bays, 2019; Cronin & Irwin, 2018). But beyond holding visual information passively (a

10   function implied by the term 'memory'), VWM is thought to be a general-purpose visual representation

11   system that is involved in a multitude of cognitive functions requiring the (active) processing of currently

12   available visual information in order to achieve the goals of the task at hand (Luck & Vogel, 2013;

13   Zimmer, 2008). Reflecting its importance as a central cognitive hub and its relation to many crucial

14   cognitive functions (Fukuda, Vogel, Mayr, & Awh, 2010; Unsworth, Fukuda, Awh, & Vogel, 2014),

15   VWM has developed, over the past decades, into a core topic in the cognitive (neuro-)sciences, sparking

16   an abundance of theoretical and methodological advances that range from general models of cognition and

17   consciousness (Block, 2011; Bundesen, Habekost, & Kyllingsbaek, 2005, 2011; Dehaene, & Naccache,

18   2001; Schneider, 2013; Soto & Silvanto, 2016; Usher, Bronfman, Talmor, Jacobson, & Eitam, 2018) to

19   the trial-wise decoding of specific mental contents from neuroimaging data (*brain reading*; Christophel,

20   Klink, Spitzer, Roelfsema, & Haynes, 2017; Harrison & Tong, 2009; Serences, Ester, Vogel, & Awh,

21   2009; Sprague, Ester, & Serences, 2014).

22   On this background, in July 2017, we hosted an international symposium on VWM at Ludwig-

23   Maximilians-University Munich, which aimed to bring together a select group of experts representing

24   different theoretical stances and methodological approaches in this rapidly growing field. Our intention

25   was to foster scientific exchange and discussions across the various viewpoints and help identify the most

26   urgent and promising questions for future research. The result did meet, if not exceed, our high

1   expectations. To make (at least some of) the spirit of this symposium available to a broader audience, we

2   decided to edit the present special issue, featuring work from many participants of the symposium as well

3   as a select number of experts who could not attend at the time. What we, hopefully, have achieved is a

4   representative, state-of-the-art overview of the field, spanning many of the various viewpoints and

5   currently debated issues.

6   To put the collection of articles into context, in particular (though not only) for readers less familiar

7   with the vibrating research on VWM, we go on to provide a selective overview on the history of the field

8   and the experimental paradigms and theoretical issues that drove and continue to drive much of the

9   research. As detailed below, all articles in the present issue, in one way or another, relate to these various

10   lines of ideas and the respective debates.

11   Most strands of psychological investigation start off with beautiful simplicity, but become more

12   complex and seemingly 'unwieldy' as research progresses. VWM research is no exception to this.

13   Originally, there was broad consensus that VWM could hold some four bound objects stored in separate

14   slots (Luck & Vogel, 1997), that the usage of VWM slots could be accurately tracked via neuronal

15   markers (Todd & Marois, 2004; Vogel & Machizawa, 2004), and that performance on the standardly used

16   *change-detection task* (Pashler, 1988) purely reflects VWM functioning, free of any extraneous factors

17   (Cowan, 2001).

18   In the (one-shot, whole-display) change-detection task, several objects (most often: coloured squares)

19   are briefly presented in a first (memory) display and after a short retention interval (typically ~1 s), a

20   second (test) display is shown. The second display is identical to the first in one half of randomly inter-

21   mixed trials, but in the other half one object has changed (typically its colour). Participants' task is to

22   decide whether a change was present or not. A simple formula can be applied to calculate, from the

23   observed error pattern, the number of objects a given participant can maintain in VWM (k; Pashler, 1988;

24   Rouder, Morey, Morey, & Cowan, 2011). Performance on this task was – in contrast to previous, largely

25   verbal, working-memory research – considered to be free from confounding influences such as long-term

26   memory and response interference, and, as all information was available in one 'snapshot', there was no

1   reason to treat the various objects differently (Cowan, 2001). However, subsequent research inspired by

2   these initial findings resulted in the accumulation of ever more data that was not easily reconcilable with

3   these initial assumptions and the original, simple theory.

4   For instance, the assumption that bound objects are held in VWM was supported by a series of

5   carefully executed change-detection experiments showing that any number of features could be stored for

6   each object with no additional costs for additional features (Luck & Vogel, 1997). This strong assumption

7   was soon challenged by studies that observed a clear decrease in performance as the number of features

8   per object increased. First, costs were shown for features from the same feature dimension (e.g., Olson &

9   Jiang, 2002; Wheeler & Treisman, 2002), for increasing object complexity (Alvarez & Cavangh, 2004),

10 and for assigning features to different parts of the same object (Xu, 2002). Further research revealed costs

11 even for features from different dimensions on the same simple-object part (Fougnie, Asplund, & Marois,

12 2010). The broadest consensus at present appears to be that, although there is some *object benefit* (i.e.,

13 more information can be stored when it is distributed across fewer objects, likely due to the features of an

14 object sharing the same location), storing additional features is not cost-free (Fougnie, Cormiea, &

15 Alvarez, 2013).

16   Whether costly or not, the brain often has to code multiple features of an object and, additionally,

17 information on which features belongs to which object (Treisman, 1996; Treisman & Gelade, 1980). This

18 *binding problem* is a recurrent theme in working-memory research and the present special issue. In their

19 contribution, Schneegans and Bays (2019) give a comprehensive overview of the binding problem in

20 visual working memory and how this problem might be solved on the neuronal level. They conclude that

21 both object benefits and costs of storing additional features can be explained by noisy, distributed VWM

22 representations of features, and that it is unnecessary to postulate a separate resource for binding features

23 within an object. Instead, features might be bound by default via their common position in space

24 (Schneegans & Bays, 2017) or time (most likely, ordinal position; Oberauer, Lewandowsky, Farrell,

25 Jarrold, & Greaves, 2012; Swan & Wyble, 2014). Whether space or time is used for binding features is not

26 easily distinguishable: when objects are presented concurrently at different positions, space can be

1   remapped onto time by sequential attention allocations (Zimmer & Liesefeld, 2011); and when objects are

2   presented sequentially at the same location, time can be remapped onto space by internally assigning

3   objects to different unoccupied locations (Abrahamse, Van Dijck, Majerus, & Fias, 2014; see also

4   Oberauer, 2009). Another hotly debated question concerns whether VWM capacity is actually limited by

5   *slots* or rather by a continuous, infinitely divisible *resource* (Bays & Husain, 2008). Schneegans and Bays

6   favour the latter assumption and explain this limit in terms of representational noise (see also Oberauer &

7   Lin, 2017; Wilken & Ma, 2004)

8   The slots-vs.-resource debate was largely based on data from a new procedure that can provide a

9   more fine-grained picture of VWM performance than the classical change-detection task: Instead of

10   comparing the memory display to a second test display, the *continuous-report task* requires participants to

11   reproduce an object feature chosen from a (virtually) continuous circular space (e.g., by choosing the

12   colour of a probed object from a colour wheel; Wilken & Ma, 2004; Zhang & Luck, 2008; or by adjusting

13   a probe object, e.g., Bays, Wu, & Husain, 2011). This task is also referred to as *analogue/cued-recall* or

14   *delayed-estimation task*. In contrast to the change-detection task, the continuous-report task does not

15   provide a binary outcome on each trial (correct vs. incorrect response), but a (virtually) continuous

16   measure: the distance between the correct feature value and the actual response (*estimation error*). Zhang

17   and Luck (2008) proposed to analyse data in this task by fitting a mixture of a van Mises (the circular

18   equivalent of a Gaussian) and a uniform distribution to the distribution of estimation errors and

19   interpreting this model's parameter values. This *mixture model* neatly fits the typically observed error

20   distribution and has since been ubiquitously applied to continuous-report data. However, several

21   arguments against the use of the mixture model have been raised (see, in particular, Ma, 2019), so that it is

22   probably advisable to analyse raw estimation errors (in addition) or to apply more elaborate, mechanistic

23   models of performance on the continuous-report task (e.g., Oberauer & Lin, 2017; Schneegans & Bays,

24   2017; Swan & Wyble, 2004).

25   Various neuronal correlates of VWM representations have been proposed. Early research identified

26   activity in/over parietal areas as measured by EEG contralateral to the remembered items (*contralateral*

1   *delay activity, CDA*; Vogel & Machizawa, 2004; for a recent review, see Luria, Balaban, Awh, & Vogel,

2   2016) or by fMRI (Todd & Marois, 2004; Xu & Chun, 2006) as a potential neuronal correlate of VWM

3   maintenance. Subsequent studies decoded VWM content from early visual areas (Harrision & Tong, 2009;

4   Serences et al., 2009). It turned out that decoding VWM content is possible from many areas throughout

5   the human brain (for a recent review, see Christophel et al, 2017). As concurrent and partially overlapping

6   activation of several neuronal populations would make it impossible to decide which features belong to

7   which objects (the binding problem), it was speculated that VWM-related parietal activity reflects a

8   pointer system, with each pointer connecting all features of one object. Indeed, the parietal activity does

9   not appear to be specific to the maintenance of visual information after it is gone; rather, it also reflects

10   processing of physically available information in VWM (Drew & Vogel, 2008; Tsubomi, Fukuda,

11   Watanabe, & Vogel, 2013).

12   As another – neuronally inspired – potential solution to the binding problem, Lisman and colleagues

13   proposed that objects are differentiated in time by differential temporal spiking patterns (Lisman &

14   Jensen, 2013; Lisman & Idiart, 1995; but see Schneegans & Bays, 2019). Neurons coding a certain feature

15   fire at a high frequency (gamma, i.e. > 30 Hz), with different representations (gamma cycles) being locked

16   to different phases of a theta cycle (i.e., 4-7 Hz). In other words, each item in VWM is repeatedly

17   reactivated (gamma) in a given order (theta). Accordingly, the coupling of gamma and theta phase has

18   been explored as a neuronal marker of VWM maintenance (Sauseng et al., 2009), and this idea was used

19   to explain capacity limits and the (purported) slot-like fashion of VWM storage: VWM capacity is limited

20   by the number of complete gamma waves that can be nested within a theta cycle of a given length.

21   Alternatively, according to a more recent proposal, items are coded as gamma bursts (i.e., multiple cycles;

22   Herman, Lundqvist, & Lansner, 2013; Van Vugt, Chakravarthi, & Lachaux, 2014) and only one item is

23   coded per theta period, with different items being refreshed in consecutive theta cycles. During a theta

24   cycle, gamma amplitude first increases and then decreases, yielding a coupling of gamma amplitude to

25   theta phase. In their contribution to the special issue, Sauseng, Peylo, Biel, Friedrich and Romberg-Taylor

26   (2019) review the pertinent cross-frequency-coupling literature and suggest that the more recent version of

1   this theory (Herman et al., 2013) and a newly proposed alternative are compatible with continuous-

2   resource as well as fixed-slots conceptions of VWM capacity. In particular, they argue that some

3   flexibility in the length of theta and/or gamma cycles yields flexibility in the number and precision of

4   VWM representations.

5   Much research has shown that not all VWM representations are created equal, and that

6   representational quality varies considerably across trials and objects (Fougnie, Suchow, & Alvarez, 2012;

7   van den Berg, Shin, Chou, George, & Ma, 2012). In their contribution to the special issue, Czoschke,

8   Fischer, Beitner, Kaiser, and Bledowski (2019) examine two sources of this variability: processing objects

9   on the previous trial(s) and processing other objects on the current trial. With a sequential presentation of

10 two objects per trial, they observe that VWM representations are attracted towards the last item on the

11 previous trial and repulsed away from the preceding item on the same trial. These effects might reflect

12 mechanisms contributing to the separation and integration of information across objects and episodes.

13   In their contribution to the special issue, Bae and Luck (2019) examine how representing a single

14 item in VWM is affected by performing a simple task during maintenance. They combine the continuous-

15 report task with the classical dual-task interference paradigm that dominated the working-memory

16 literature before research on VWM gained momentum (Baddeley, 1986; Logie, 1995). In this paradigm,

17 participants have to perform a secondary task during working-memory maintenance, which is supposed to

18 either draw or not draw on the same working-memory system or component. Bae and Luck's results show

19 that processing a letter deteriorates the representation of a single orientation, in that it becomes less precise

20 and biased more strongly away from cardinal orientations (see also Hardman, Vergauwe, & Ricker, 2017).

21 No such effect is found for processing an auditory stimulus during single-orientation maintenance. This

22 dissociation indicates that processing information from the same modality displaces the VWM object from

23 a special state ('focus of attention', see Oberauer, 2002; Oberauer & Lin, 2017), leaving only a relatively

24 coarse representation. Having to remember only one item on each trial is critical in this study, because this

25 rules out interference from other items on the same trial. Bae and Luck's study also nicely demonstrates a

26 major strength of the continuous-report task: it provides a particularly sensitive measure of subtle effects

1   on VWM performance. Remembering only one object would produce ceiling performance in the change-

2   detection task, making it impossible to examine effects on the representation of a single item.

3   In their contribution to the special issue, Tabi, Husain and Manohar (2019) demonstrate a drawback

4   of a standard version of the continuous-report task, which requires participants to adjust a memory probe:

5   performance improves if the probe object is initially set to neutral with respect to the probed feature,

6   instead of taking a random feature value as is common practice in this paradigm. Thus, processing the

7   random probe feature likely partially overwrites the probed memory representation. A similar interference

8   is likely induced by the commonly employed colour wheel (Souza, Rerko, & Oberauer, 2016). Tabi et

9   al.'s new method to start off with a neutral probe is designed to eliminate this source of interference by

10   allowing participants to first transfer the probed feature into a more robust state (see Souza et al., 2016, for

11   a related effect of retro-cues, i.e., cues given during the retention period before the test).

12   Probably, such interference does not occur in the change-detection task. One potential interpretation

13   of the whole-display change-detection task is that the onset of the test display produces a spatial

14   representation akin to a saliency map in visual search that (noisily) encodes the mismatch with the

15   memorized display, with registration of a mismatch signal being used to decide upon the presence of a

16   change (Hyun, Woodman, Vogel, Hollingworth, & Luck, 2009; Liesefeld, Liesefeld, Müller, & Rangelov,

17   2017). On that account, the interference by the test display would occur only after the critical mismatch

18   signal is already produced, so that the change-detection task would indeed provide a relatively pure (albeit

19   coarse) picture of VWM performance (but see, Alvarez & Thompson, 2009).

20   A further advantage of the change-detection task is that, in addition to accuracy, it allows reaction

21   time to be examined as a measure of the speed of comparing VWM entries with visual input (Donkin,

22   Nosofsky, Gold, & Shiffrin, 2013; Gilchrist & Cowan; Hyun et al., 2009; Liesefeld et al., 2017; Park,

23   Zhang, & Hyun, 2017). The interpretation of reaction times is less straight-forward in the continuous-

24   report task, because it takes quite some time until a response is selected and executed (moving the arrow

25   to the position on the colour wheel or toggling through all values with the probe), allowing for all kinds of

26   confounding influences and measurement noise (see, e.g., Tabi et al., 2019). Thus, the two tasks have

complementary strengths and weaknesses and can provide different perspectives on VWM performance, and comprehensive models of VWM should explain performance on both (and other, e.g., localization, Liesefeld, Liesefeld, & Müller, 2019; van den Berg et al., 2012) tasks.

An (unwanted) source of variability in all types of VWM tasks arises from the possibility that people do (at times) not only represent individual objects, but (additionally) what several objects in the display have in common. This might include maintaining chunks of information (Miller, 1957; Morey, Cong, Zheng, Price, & Morey, 2015; Peterson & Berryhill, 2013; Quinlan & Cohen, 2012) or ensemble representations (Brady & Alvarez, 2011, 2015a,b; Brady & Tenenbaum, 2013). In the classical colour change-detection task, repetition of colours within a display provides opportunities for such compressed representations. In her contribution to the special issue, Morey (2019) directly manipulated the potential for compression by presenting up to three objects of the same colour. She observed increased detection rates for these redundant objects and also – in young, but less so in older adults – a spill-over of VWM capacity to objects with unique colours. Furthermore, using pupil dilation as a marker of mental effort, she found decreased effort with increasing redundancy in young participants.

In our contribution to the special issue (Liesefeld et al., 2019), we tried to minimize opportunities for compressed coding by explicitly avoiding colour repetitions within a display. Still, even in this purest version of the standard colour change-detection task, we find indications for the involvement of ensemble representations. In particular, we additionally asked participants to localize the change and compared localization performance to change-detection performance using mathematical models. The model providing the best account of our data indicates that VWM capacity is routinely overestimated when considering only change-detection performance and that VWM can actually hold only about 2.3 individual items, which contrasts with earlier estimates of 7±2 (Miller, 1957) or, respectively, 4±1 (Cowan, 2001) items. Given that a privileged, focal-attentional state (Bae & Luck, 2019; Oberauer, 2002; Oberauer & Lin, 2017) holds 1 of these 2.3 items, the capacity estimate for 'usual' VWM would effectively shrink to (a little over) 1 item.

1   Speculations about multiple, qualitatively different VWM states (see also Cowan, 1999; Oberauer,

2   2002) prompt another potential solution to the binding problem (or rather its dissolution). If 'usual' VWM

3   indeed can hold only one item, one item is in the focus of attention, and any additional information is

4   coded as an ensemble, one needs to assume only one representation in each state to explain typical

5   estimates of VWM capacity of around 3 items. Consequently, there is no further need to keep features

6   from an object bound together and apart from other objects. The notion that a multitude of qualitatively

7   different representations, at different levels of abstraction, contribute to performance on VWM tasks

8   would be in line with recent neuroimaging evidence for VWM representations in several, distributed brain

9   areas (Christophel et al., 2017). The ever-increasing list of contributors to performance on VWM tasks

10   also hints at a general "problem" in cognitive science: humans are highly adaptive and exploit whatever

11   cognitive resources they have at their disposal to solve a given (laboratory) task without regard to the (by

12   the scientist) targeted cognitive construct and the aesthetically pleasing simplicity of cognitive theories

13   (see also Zimmer & Liesefeld, 2011).

14   Not only does attention affect VWM performance (by raising one item to a special state; Griffin &

15   Nobre, 2003; Oberauer, 2002; Oberauer & Lin, 2017; Souza & Oberauer, 2016), but VWM is also thought

16   to influence attentional dynamics. One common assumption is that an item in the special state operates as

17   a *search template* (Duncan & Humphreys, 1989; Hollingworth & Hwang, 2013; Olivers, Peters,

18   Houtkamp, & Roelfsema, 2011; Schneider, 2013). In their contribution to the special issue, Berggren and

19   Eimer (2019) examine how storing shapes in VWM conflicts with spatial templates (i.e., maintenance of

20   potential target locations). Using an electrophysiological marker of attention allocations (N2pc; Eimer,

21   1996; Luck & Hillyard, 1994a,b), they observe a delay in attention allocation towards the target when

22   VWM load is high, indicating that VWM for shapes and spatial templates share a common resource.

23   Working memory also appears to be involved in the familiarization with visual-search scenes. It has

24   been shown that repeating spatial stimulus configurations ('context') speeds up the search due to

25   incidental long-term learning of spatial distractor-to-target relations (*contextual cueing*). In his

26   contribution, Pollmann (2019) reviews the literature on the involvement of spatial working memory in the

1   contextual-cueing effect. Various studies have shown that spatial working-memory load can disrupt the

2   effect. This is, however, true only if applied during the test phase of the task, indicating that spatial

3   working-memory load does not impede the acquisition of contextual information; rather, the retrieval of

4   this information from long-term memory operates via working memory and may thus be hampered by

5   spatial working-memory load. In their contribution, Annac, Zang, Müller and Geyer (2019) report that this

6   is not necessarily the case: the working-memory bottleneck can be bypassed as a result of training. That is,

7   after an extended period of training, the contextual-cueing effect was found to emerge even with

8   concurrent working-memory load during test. Surprisingly, Annac et al. even observed an amplification of

9   the contextual-cueing effect by concurrent working-memory load, indicating that, under these conditions,

10   context information may be directly retrieved from long-term memory (see Reinhart, McClenahan, &

11   Woodman, 2016, for a related finding).

12   　　　Another core topic in VWM research are interindividual differences in VWM capacity and whether

13   capacity is fixed or can be boosted (Fukuda et al., 2010; Liesefeld, Liesefeld, & Zimmer, 2014; Unsworth

14   et al., 2014; Vogel & Machizawa, 2005; Vogel et al., 2005). Sauseng et al.'s (2019) review discussed

15   above summarizes evidence that entrainment of certain theta frequencies via electrical cortical stimulation

16   can increase (slower theta) or decrease (higher theta) VWM capacity (Vosskuhl, Huster, & Hermann,

17   2015; Wolinski, Cooper, Sauseng, & Romei, 2018). But we don't need to turn to cortical stimulation to

18   improve VWM performance. In their contribution to the special issue, Dodwell, Müller and Töllner (2019)

19   examine how moderate aerobic exercise (vs. passive control) and body posture (upright on a treadmill vs.

20   seated on a bike) while performing a speeded VWM task influence separable VWM processes. Exercise

21   and upright posture speeded reaction times compared to passive (resting) and seated conditions,

22   respectively. Examination of electrophysiological markers revealed that this reaction-time advantage was

23   not due to faster VWM access, but rather to expedited processes of selecting the appropriate response to

24   the target representation held in VWM.

25   　　　Finally, the relation between stimulus material and the observer, such as familiarity (Curby &

26   Gauthier, 2007; Curby, Glazek, & Gauthier, 2009; Jackson & Raymond, 2008) and emotional content

(Jackson, Linden, & Raymond, 2014; Jackson, Wu, Linden, & Raymond, 2009; Kensinger & Corkin, 2003; Maran, Sachse, & Furtner, 2015; Mather, 2007), also influences VWM performance. In their contribution, Curby et al. (2019) report a detrimental effect of fearful faces on VWM capacity that is consistent across four experiments. This is particularly notable, as earlier research had more often found VWM benefits, rather than costs, for emotional (including fearful, angry, sad, and happy) faces (e.g., Jackson et al., 2009, 2014; Sessa, Luria, Gotler, Jolicoeur, & Dell'acqua, 2011). Curby et al. test and discuss in great detail how effects of emotion on VWM performance are modulated by subtle differences in task designs (such as encoding duration and set size) and/or by the processing and maintenance of different emotions.

The collection of articles is rounded off by an integrative commentary by Rhodes and Cowan (2019) that we have not yet received at the time of writing this introduction. It will be of interest to the reader to compare the overlap of our introduction with their commentary.

Although some current topics, such as the active manipulation of VWM content (e.g., Christophel, Cichy, Hebart, & Haynes, 2015; Liesefeld & Zimmer, 2013) and the relationship of LTM and VWM (e.g., Brady, Störmer, & Alvarez, 2016; Schurgin, Cunningham, Egeth, & Brady, 2018) are not represented here, we believe that reading through the articles in this issue provides a relatively comprehensive overview on the current state of VWM research. In any case, we are proud to present this collection of articles to the readers of the *British Journal of Psychology* and thank the editor-in-chief, Stefan Schweinberger, for giving us the opportunity to compile this Special Issue. We hope that you all enjoy reading it as much as we enjoyed putting it together!

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