Enhancing Cognitive Conversion: The Impact of Sensory Stimuli on Visual Working Memory and Future Applications

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Keywords: Visual Working Memory (VWM), Sensory Stimuli (SS), Cognitive Development, Artificial Intelligence (AI) and Reinforcement Learning (RL).

Abstract: Visual working memory (VWM), a crucial short-term and long-term memory component, underpins cognitive performance and daily life. This study proposes optimizing VWM formation by strategically designing sensory stimuli (SS) to enhance the cognitive conversion from sensory memory to VWM. The present study hypothesizes integrating various SS parameters based on a systematic review of previous research to improve the VWM's overall performance, including attentional selection and VWM consolidation. It also highlights the conducive role of multi-ss interactions in expanding the potential of improving cognitive conversion. Targeting the optimal period for cognitive development, this research focuses on children to maximize the potential for enhanced thinking abilities. The improved cognitive conversion in VWM formation may serve as an effective intervention for cognitive impairments. To personalize training and adapt to individual cognitive growth, this study explores the incorporation of AI markers and Reinforcement Learning (RL) into smart toys, providing dynamic feedback and optimizing VWM development during interactive play. However, there are still some challenges at play considering the speciality of the targeted children population and the VWM mechanism's complexity. This research suggested some suggestions, underscoring the value of flexible interdisciplinary method transformation.

1 INTRODUCTION

Visual working memory (VWM) is a cognitive powerhouse that temporarily stores and manipulates visual information (Ware, 2013). It is a last stage in Visual Short-Term Memory (VSTM), where the order is: iconic memory, fragile VSTM, and VWM. Each characterized by different capacities and durations: iconic memory serves as a high-capacity buffer for transient sensory information immediately after stimulus presentation, while VWM has more stringent capacity limits, typically accommodating approximately 2-4 objects for longer retention (Sligte, 2010). The active VWM process may be primarily responsible for the retention of knowledge about the 10-item array over 1000 ms (Bradley and Pearson, 2012). This progression highlights the crucial role of understanding the transition from sensory memory to VWM. VWM's capacity is limited but can be modulated by stimulus characteristics, encoding strategies, and individual differences. Understanding the impact of SS on VWM increases efficiency by allowing us to apply the appropriate sensory stimuli to the appropriate tasks.

The way SS is encoded is highly dependent on the sensory features present in a stimulus. So, by manipulating SS, we can directly influence the encoding process, leading to improvements in storage of information in VWM. Therefore, it is meangful to explore the impact of SS on VWM.

This study first summarizes and integrates relevant current studies on conversion efficiency to VWM. Next, this study will propose potential future applications in three dimensions based on the stimuli and the process. Incorporating the cognitive differences across different age groups, this study will explore the design of an improved user interface and experience, with a particular focus on promoting early cognitive growth and preventing mental diseases associated with cognitive decline. Furthermore, this study innovatively proposes the potential of incorporating AI markers into these designs to predict cognitive boosts and decreases. This approach has the potential to not only offer valuable guidance for improved prevention, providing reassurance about the study's practical implications, but also to create an adaptive learning system that caters to individual needs. RL allows AI

Chen, Q.
Enhancing Cognitive Conversion: The Impact of Sensory Stimuli on Visual Working Memory and Future Applications.
DOI: 10.5220/0014111300004942

In *Proceedings of the 2nd International Conference on Applied Psychology and Marketing Management (APMM 2025)*, pages 217-222
ISBN: 978-989-758-791-7

systems to iterate, categorize, and analyze real-world data more effectively and accurately during human-AI interactions.

2 THE IMPACT OF SS ON VWM

2.1 Theoretical Foundations of VWM Formation

VWM formation begins with the sensory processing of visual input (VI) by the eyes (Atkinson and Shiffrin, 2024). This initial input creates IC, a brief, high-capacity sensory buffer where salient features are prioritized even pre-attentively. Because VWM has limited capacity, attention acts as a critical filter, selectively transferring information from IC to create visual working memory representations (VWMR). This transfer is goal-directed and shapes VWMR, determining the format and structure of the visual information retained. These representations, which can be static or dynamic, are actively maintained and manipulated through the interaction of a distributed brain network. Sensory areas initially encode the visual information Therefore, the SS of the initial VI are crucial in shaping the content and fidelity of the resulting VWMR. The limitations of VWM arise in part from the capacity to process this sensory information, highlighting the importance of efficient selection for successful memory formation.

2.2 Analysis of Specific Visual Properties' Impact on VWM

Research suggests that several key visual attributes, including spatial frequency, orientation, motion, contrast, and color, significantly influence VWM (Magnussen, 2000).

2.2.1 Speed of Dynamic VI

Recent research indicates that the precision of VWM responses is significantly higher for moving stimuli compared to stationary stimuli (Chung et al., 2023). This enhanced precision, though with a slight temporal lag, supports the hypothesis that object motion facilitates the integration of object information over extended periods. This notion aligns with findings from memory masking experiments, which have shown that VSTM for motion primarily encodes the speed of the stimulus, rather than its spatial or temporal frequency content (McKeefry et al., 2007). Given that VWM is considered to be embedded within VSTM, the speed of a moving stimulus should be regarded as a critical motion-related SS feature for optimizing VWM research and application.

2.2.2 Color

When it comes to VWM and object recognition, colour is crucial. Understanding the mechanism of the visual cognitive process and assessing memory capacity are made easier with the help of colour VWM decoding in the human brain. Target letters in an n-back task were changed into Baker-Miller pink, blue, red, or black in one behavioural experiment that assessed working memory performance (Galvez, 2015). It was found that the color had no effect on accuracy, but red is the most easily caught by attention. Recent research has identified different representations of specific sensory features (like color) in VWM can be measured using scalp electroencephalogram (EEG). The accuracy of colour decoding during the encoding, early, and late maintaining stages was 81. 58%, 79. 36%, and 77. 06%, respectively. These decoding accuracy levels were higher than those during the pre-stimuli stage (67. 34%), and during the maintaining stage, they may predict the memory performance of the participants. The EEG colour graph convolutional network (ECo-GCN) model offers a useful method for investigating human cognitive function, and EEG data during the maintenance stage may be more sensitive than behavioural testing to predict human VWM performance (Galvez, 2015). In the future study, EEG may further explore the performance of various color decoded from encoding process, thus finding the best color for SS design.

So far, there is little research indicating what kind of orientation, and geometric features may be beneficial to VWM. Future study may explore further regarding this field.

2.3 SS Through IC

In both retinotopic and non-retinotopic frames of reference, researchers have found that the contents of IC can be altered by later VI before being translated into conscious awareness in a time-locked manner. This means that new VI can affect objects and spatial locations. Additionally, the IC can revise its contents based on the configuration of the new representation, causing the original sensory representation to be altered or updated before being selected for visual processing machine, namely VWM. This can lead to an incongruity between the initial sensory experience and the encoded information in the VWM. Therefore, it should be noticed that there is a close interplay between early sensory processing and later cognitive processes , which is the conversion from IC to VWM. The quality of information in IC directly affects the quality of the VWMR. While IC appears to encode motion information less effectively than color or orientation, the inclusion of moving information has a beneficial impact on long-term memory (LTM) (Bradley and Pearson, 2012 & Che et al., 2022). Given VWM's intermediate position between iconic and LTM, careful consideration must be given to the specific effects of different sensory features during the stimulus design to optimise memory at all stages.

2.4 Multi-SS Interaction

Researchers have underscored the significance of multi-ss interaction in positively improve VWM process.

To begin with, researchers have found the effect of sensory stimulation, where both visual and auditory stimulation at frequencies of 4 Hz and 7 Hz significantly improved VWM performance compared to baseline conditions. A combination of the 4 Hz and 7 Hz conditions into a single stimulation revealed a significant increase in VWM capacity (Matthews et al., 2007). The calibration of SS targeted to address VWM deficits of limited capcity, thus highlighting the promise of using sensory stimulation as a tool for cognitive enhancement

Moreover, according to the current study, performing a visual orientation sequence task significantly improved after practicing a tactile sequence task. We showed that switching from a tactile to a visual task could have a beneficial training effect. It was also possible to apply this training effect to other behavioural tasks that included the same cognitive processes (Pileckyte and Soto-Faraco, 2024). This enlightens us to combine various SS like tactile sense to achieve an elaborated design of smart toys for different purposes.

2.5 Other Conditions of SS that Influence the Performance of VWM

Beyond core stimulus attributes, emerging evidence reveals other SS conditions significantly modulate VWM. For instance, VWM capacity improvements are linked to modulated temporal expectations, not just periodic entrainment (Matthews et al., 2007), highlighting the influence of temporal context. Distractors also introduce biases in VWM representations based on similarity, interacting with maintained information (Guo et al., 2021). Furthermore, more meaningful stimuli recruit additional VWM resources, facilitating retention (Teng and Kravitz, 2019). Even categorical reporting biases are heightened following unattended storage, with biased gaze patterns emerging during maintenance (Asp et al., 2021). Importantly, the degree of congruency between sensory features, both within and across modalities, influences VWM encoding; congruent multi-SS may be encoded more readily, while incongruent stimuli may require more processing resources, potentially negatively impacting VWM performance (Linde-Domingo and Spitzer, 2023). These findings collectively demonstrate that various SS conditions beyond basic attributes powerfully influence VWM, by impacting encoding, maintenance, and retrieval.

Furthermore, attentional allocation across sensory modalities profoundly shapes visual information processing and storage in VWM. Distributing attention across multiple modalities significantly alters audiovisual processing (Linde-Domingo and Spitzer, 2023), and recent findings indicate that occipital, parietal, and frontal cortices selectively maintain task-relevant features (Mishra and Gazzaley, 2012). These findings demonstrate that attentional allocation must be controlled when manipulating SS.

Last but not least, a study found that highly discriminable sensory features were encoded into VWM via an object-based effect(OBE), leading to prolonged search time. The study also revealed that the initial encoding is not "smart" as VWM takes in a holistic representation of an object with all its sensory features. Task-irrelevant information is still processed and affects performance, even if it is not task-relevant (Yu and Shim, 2017). In addition, the capacity of VWM must be understood in terms of integrated objects rather than individual features. At least four features can be joined in this manner with no cost in terms of storage capacity (Luck and Ford, 1998).

This has implications for stimulus design in studies relying on VWM, as it is impossible to only process the intended task-relevant information. It needs to design SS with a low amount of irrelevant sensory information to improve performance.

3 FUTURE APPLICATIONS

SS play a pivotal role in the transition from IC to VWM, significantly influencing cognitive processes. The potential future applications of this understanding are vast and promising.

3.1 Strength in Children—Better Brain Activation

When researchers compared performance between update and non-update trials in a 2-back task, they discovered that VWM deficits increased with age. Older people exhibited reduced neuromodulations to the working memory updating process in the task-sensitive areas in addition to performance losses (Qin and Basak, 2020). Therefore, children show potential for a boost in the formation of VWM.

3.2 Practical Implications

3.2.1 User Interface and Experience Design

Integrating visual colours and geometric shapes into user interface designs can improve usability and accessibility by making information more engaging and easier to process. As educational paradigms evolve, integrating multi-sensory theory into the design of children’s educational toys presents a promising avenue for enhancing learning outcomes (Fan et al., 2024). Instructional visualizations should be designed to manage this balancing act and to support information processing optimally (Brucker et al., 2014). That, in particular, prospects promising development in (1) Cognitive Development in Early Childhood and (2) Cognitive Health and Well-being of children.

(1) Cognitive development in early childhood

Developing multi-sensory learning strategies through the use of tactile materials (e. g. three-dimensional geometric shapes) or learning tools with sound effects can promote children's all-round, multi-sensory cognitive development. Optimising the visual design of classroom environments The overall design of the classroom can also take into account the SS to create an environment that is stimulating to the senses and promotes learning.

(2) Cognitive health and well-being.

Tactile stimulation training could partially reverse age-related cognitive decline among older adults and increase processing speed in younger participants (Reuter et al., 2014). Developing cognitive training tools and interactive games that leverage visual colours and geometric shapes can stimulate cognitive functions and help prevent conditions like dementia in older adults. Integrating visual and geometric stimuli in therapeutic programs can aid in rehabilitating cognitive functions in children with cognitive impairments (Wang et al., 2021).

3.2.2 Artificial Intelligence and Machine Learning

As robust and interpretable AI-guided marker has been built for early dementia prediction in real-world clinical settings and the ability of both memory and thinking change with age, utilizing visual colours and geometric shapes as markers in AI appear to be possible in better understanding the process of cognitive development and establishing adaptive learning systems (Kale et al., 2024 & Harvard Health Publishing, 2017). For example, AI markers integrated into children’s educational toys can track and analyze children's cognitive development, identifying key developmental milestones and intelligence boosts. At the same time, adaptive learning systems that modify visual and geometric content based on a learner's cognitive level can provide personalised challenges, enhancing cognitive development and retention of complex concepts. Long-term observation of the training effect can be shown by rising trends of grades of difficulty in the design of SS and children's performance, as the improved accuracy of VWM through training may partially transfer to more VWM tasks with other stimuli (Bi et al., 2020).

Further, it is beneficial to AI systems as well. They can categorize and analyze data more effectively and accurately by RL in recording long-term pattern recognition trials, enhancing the overall performance of AI-driven data analysis.

Recently, researchers discovered that, compared to a conventional motor-only paradigm, the multi-modal technique maintained consistent engagement by EEG biomarkers. That highlights the benefit of a comprehensive robotic intervention combining motor, cognitive, and auditory functions (Oliver et al., 2024). Incorporating the fundamental principles of VWM and the various characteristics of cognitive development stages into "Smart Toys" design for human-computer interaction can significantly improve cognitive development efficiency. By going beyond simple, functional interactions, these toys can be enhanced by integrating memory formation principles, ultimately fostering greater cognitive growth.

3.3 Influential Factors for the Capacity of Forming VWM in Children

3.3.1 Cognitive Load and Interference

VWM load has a late neuronal response on auditory stimuli, which reduces the likelihood that these SS will be reported (Brockhoff, 2023). VWM performance may be hampered by auditory stimuli when there is a significant cognitive load. The efficacy of memory tasks may be hampered when visual and aural cues vie for processing resources (He et al., 2022). In children, managing cognitive load effectively is vital for optimizing learning outcomes and ensuring that sensory information is appropriately encoded into VWM.

3.3.2 Complexity of VI

The complexity of VI plays a significant role in how well children can encode information into VWM. Studies manipulating figural complexity have shown that as complexity increases, distinguishing between target and probe stimuli becomes more challenging for young children (Suda et al., 2024). This indicates that simpler, well-defined shapes and colors may facilitate better encoding and retention in VWM.

3.3.3 Dynamic Coding Mechanisms

Research suggests that dynamic coding may help separate SS from VWM contents during tasks requiring memory maintenance. This mechanism allows for effective encoding and retrieval of information while minimizing interference from ongoing sensory stimuli (Degutis et al., 2024). Understanding how these dynamic processes operate in children could lead to better educational strategies that leverage multi-sensory approaches.

4 CONCLUSION

This study seeks to elucidate the impact of SS on VWM and its potential applications for both human enhancement and artificial intelligence. Synthesizing existing research on optimizing SS for VWM formation, this research proposes that dynamic, congruent multisensory stimuli incorporating appropriate visual speed represent a promising avenue for future exploration. The identified features that enhance VWM formation have direct practical implications, particularly for the design of smart toys for children and the development of more robust AI systems.

The novelty of this research lies in its systematic approach to summarizing key SS features that influence VWM. This study addresses a significant gap in the current design of many smart toys, which often prioritize aesthetic user interfaces and diverse content while overlooking the scientific principles underlying VWM formation. This finding highlights the potential of multi-SS design and the utilization of AI-markers in smart toy programming to enhance learning and cognitive development.

To mitigate bias related to individual sensory preferences, including color, investigations into personal preferences should precede any behavioral experiments. Furthermore, this research strongly advocates for the use of other advanced brain imaging research methods represented by EEG in future studies to achieve a more precise and nuanced understanding of the neural mechanisms underlying VWM responses to different SS features. This approach could lead to more personalized and effective designs. Future research should aim to establish a more precise and generalizable multi-SS model, incorporating the various identified sensory features to maximize VWM performance.

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