Bachelor Thesis

The Capacity and Structure of Visual Working Memory: Testing New Concepts

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Abstract

The capacity and structure of visual working memory (VWM) have become widely debated topics with a focus on two distinct theories: discrete-capacity and limited-resource models. The discrete-capacity object-based views conceptualise the capacity of VWM as a limited number of “slots”, each storing a single object encoded as a unitary item with all of its features. Once all the slots are filled, additional objects cannot be encoded. In contrast, limited-resource feature-based views hold that separate features rather than unitary objects are being encoded and that the capacity of VWM is not restricted to an upper limit of items. Instead, VWM capacity is conceptualised as a limited resource which is flexibly distributed among the items in the scene; the recall precision gradually decreases with the increase in the number of features. Discrete-capacity object-based views and limited-resource feature-based views were put to the test in the present study by using a delayed-estimation task. The participants were presented with a varied number of stimuli and asked to attend to their colour, orientation, or both. The precision of their recollections was measured. The results provide evidence against discrete-capacity models and show that the recall precision is already imperfect under the previously proposed item limit. As expected according to limited-resource feature-based view, the precision continuously decreased when the set size was increased and varied depending on the attended feature. However, the unpredicted absence of a decrease in precision between orientation and colour and orientation conditions suggest that the concept of VWM having a single resource pool does not provide a complete explanation and point towards the existence of independent pools of resources for different features.

Introduction

Visual working memory (VWM) is defined as the ability to temporarily store and manipulate currently relevant visual information and is considered to have a limited capacity (e.g., Bocincova & Johnson, 2019; Yatziv & Kessler, 2018). At the present time, conflicting theories, explaining how VWM operates and what its capacity is, exist. Therefore, the present study aimed to explore the opposing theories and examine which one is the most plausible on the basis of current findings. The pioneer researchers of working memory suggested its capacity to be a fixed number of items, such as Miller's seven, plus or minus two (Miller, 1956), or, later, Cowan's four (Cowan, 2001). These studies were based on discrete-capacity models which suggest that the precision of VWM can be measured using the notion of available storage places or *slots*. If an object occupies a slot, it is accurately recalled with all of its features, regardless of whether it has one single feature or four (Luck & Vogel, 1997). In case the object does not get into the slot, it is not remembered all.

The findings of recent studies contradict discrete-capacity models and offer support for the conceptualization of the capacity of VWM as qualitative rather than quantitative. Recent studies found that the memories of objects become gradually noisier as the number of features to be remembered is increased, challenging the object-based view of VWM organisation (Hardman & Cowan, 2015; Ma, Husain, & Bays, 2014; Park, Sy, Hong, & Tong, 2017; Wilken & Ma, 2004). On the basis of the concept of memory noise, the objects are not binary encoded versus not encoded; instead, they are encoded with a certain amount of precision, which can be measured continuously (Ma et al., 2014; Shin & Ma, 2017). Limited-resource models have been proposed as an explanation for these findings according to which the capacity of VWM is defined as a limited resource which can be distributed flexibly across objects. Whereas discrete-capacity models would predict no differences in error between different numbers of presented objects under a certain capacity limit and a steep decline in recall performance once that capacity limit has been reached, limited-resource models predict errors to occur even before the previously suggested capacity limit is reached and that the recall variability would gradually increase as the size of the presented set is increased (Ma et al., 2014). Hence, according to the continuous-resource models, the recall performance is determined by the quality rather than the quantity of VWM representations.

Closely related to VWM capacity is the debate concerning visual attention, specifically, whether its units are objects as a whole or separate features of an object. Visual attention can be considered as a cognitive filtering mechanism that selects the relevant visual information for further processing in VWM (Brummerloh, Gundlach, & Müller, 2019; Jonikaitis & Moore, 2019; Park et al., 2017). The findings of the early studies (e.g., Miller, 1956; Cowan, 2001) led to the development of an integrated object account which, in line with discrete-capacity models, holds that when an object is encoded, all of its features are maintained as a coherent unit (Luck & Vogel, 1997; O'Craven, Downing, & Kanwisher, 1999; Park et al., 2017). Thus, all the features that constitute an object are attended to and stored in VWM, regardless of their task-relevance (Brummerloh et al., 2019). However, the findings of recent studies challenge the integrated object account and demonstrate that the representations in VWM can be broken down into individual features (Brummerloh et al., 2019; Park et al., 2017). In some studies it has been observed that attended features are stored with higher precision at a cost of the accuracy of the remaining features of the stimulus, which contradicts the notion of binary slot encoding (Bocincova & Johnson, 2019; Ma et al., 2014; Markov, Tiurina, & Utochkin, 2019; Park et al., 2017; Shin & Ma, 2017). Accordingly, in case the instructions to attend a certain feature are provided, that feature is recalled better as compared to when no specific instructions are provided. These findings oppose the integrated object account predictions that such attentional instruction would have no impact on the recall variability.

The variability in VWM precision is commonly tested using continuous stimulus and response spaces, such as delayed-estimation technique (Ma et al., 2014). In this task, the participants are required to report a certain feature of a location-probed item (e.g., colour or orientation) based on their memory of the item (e.g., see Yatziv & Kessler, 2018; Ma et al., 2014; Park et al., 2017). This design allows measuring the precision of the response as a deviation from the correct answer on a continuous scale (Oberauer & Lin, 2017; Yatziv & Kessler, 2018). In contrast to change-detection tasks, continuous-reproduction tasks as such provide information about the quality of the memory rather than a binary score of correct or incorrect recall.

An important consideration when constructing the delayed-estimation task design is the discrepancy between the physical description of the changes in stimuli features and how those changes are perceived by an individual. Whereas the changes in the physical values of the features (e.g., angles in orientation) are linear, the perceived changes have scales with a unique shape for each different feature and individual (Kingdom & Prins, 2016, p. 23; Stevens & Galanter, 1957). Consequently, in case linear scales of feature changes are used (e.g., see Oberauer & Lin, 2017), the increases in errors are not linearly spaced. To correct for non-linearity of errors, it is important to equate the distances of the perceptual change by determining the individual scales of perception of feature changes, which can be done by constructing an individual set of barely distinguishable features for each participant.

Aim of the Study

In order to test the predictions of discrete-capacity and limited-resource models and object- and feature-based views, the aim of the present study was to explore how the recall precision of the multi-feature items is affected by attentional instruction and set size. As a means to test the two conflicting theories, a delayed-estimation design preceded by a sensitivity test was employed with either one, two, or four stimuli presented at a time. To test the effects of feature-specific attention, the present study used stimuli constructed of two features, colour and orientation (Bae, Olkkonen, Allred, Wilson, & Flombaum, 2014), to create three different conditions, in which the participants were instructed to attend to only the colour, only the orientation or both. In accordance with most recent theories which suggest that the units stored in VWM are single features of the object rather than a whole unified object, as postulated by an integrated object account, it was expected that the stimuli will be recalled with higher precision when the participants are instructed to attend only one of the features in contrast to when they have to attend to both. In addition, in line with limited-resource models, it was hypothesized that the recall variability will increase gradually when the set size of the stimuli features is increased, contradicting discrete-capacity models. The results that would be expected to be observed based on both discrete-capacity object-based view and limited-resource feature-based view are depicted in Figure 1.

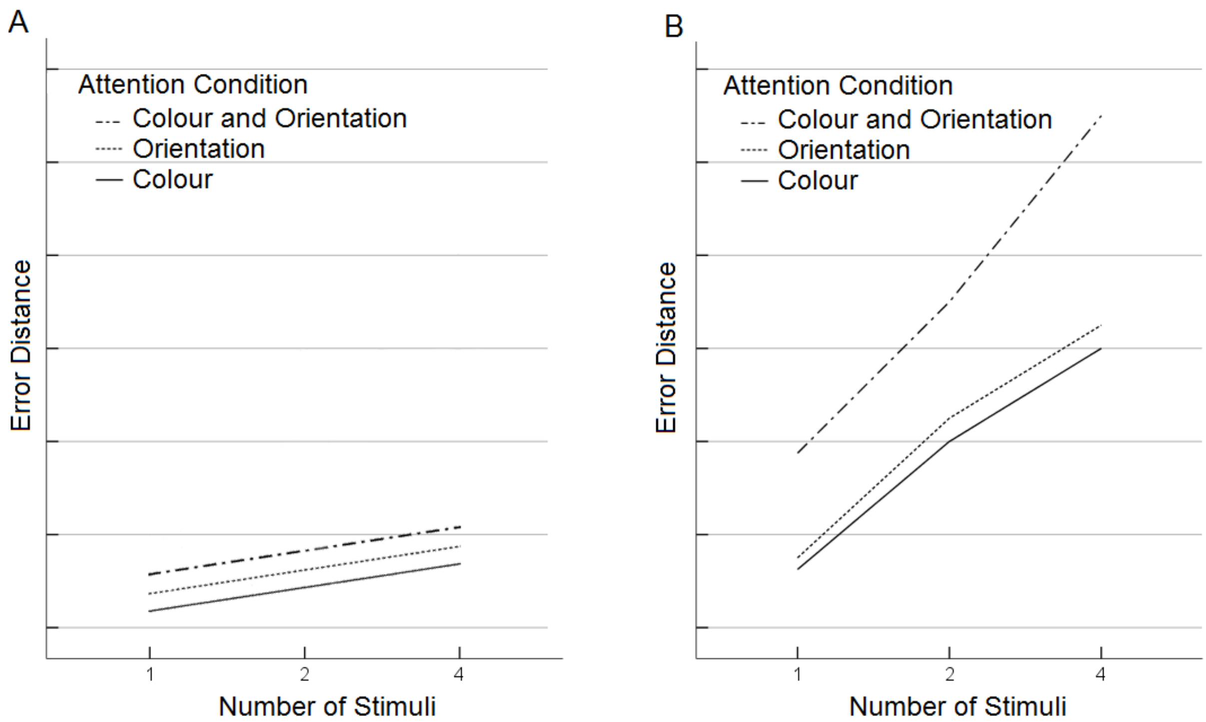

Figure 1. The visualisation of approximate predictions based on the two distinct models of VWM capacity and structure. (A) Predictions of object-based discrete-capacity models. No distinction in errors would be expected to be observed regardless of the attentional instructions provided or number of stimuli presented. (B) Predictions of the current study on the basis of feature-based limited-resource models. The single-feature attentional conditions are expected to result in comparable accuracy, whereas when both features have to be attended, the error is expected to be significantly higher and display a sharp increase due to the exponential increase in the features to be memorised.

Method

Participants

Eighteen students from the University of Twente participated in exchange for course credits (M_{age}= 22.1, range: 19-29 years; 7 female; 16 right-handed, 2 left-handed). The data of one of the participants were replaced due to the participant not being able to distinguish the required number of orientations within the given set during the sensitivity test. All of the participants reported normal colour vision, which was confirmed with an online colour-blindness test (“Ishihara 38 Plates”, n.d.), and all had normal or corrected to normal visual acuity, which was tested using Landolt C stimuli (Bach, 2007). The experiment was approved by the Faculty of Behavioural, Management and Social Sciences ethics committee of the University of Twente and all participants provided written informed consent.

Materials

Stimulus presentation and data collection were performed using Spyder® 3.2.8 development environment for Python 2.7 on a desktop computer running under Windows 10. All parts of the experiment were presented from a viewing distance of 50-60 cm on a 24-inch screen, with 1920 by 1080 pixel resolution and 16:9 ratio on a light grey background.

The stimuli used were circle gratings of a 4.5° radius composed of two distinct features – colour and orientation. The colour set consisted of 40 values which were sampled from an HSV colour space with the hue ranging from 0° to 39° and intensities of saturation and value fixed at 80% (Fig 2). The orientation of stimuli spanned from 19° to 79° rotated clockwise from a vertical grating position (Fig 2).

Procedure

At the start of the experiment, participants received written instructions and signed the informed consent form. After the preliminary tests of colour-blindness and visual acuity, the participants completed the colour sensitivity test in order to determine the individual list for each participant consisting of the five most similar colours between which they could distinguish. During this part, the fixation cross was presented in the centre of the screen with the two gratings appearing at a 1.5° distance from the cross. The first stimulus appeared on the left side of the fixation cross for 1000 msec followed by the second stimulus presented for 1000 msec on the right side of the fixation cross. At the beginning of the colour sensitivity test, one of the stimuli had a hue of 0° and the other of 1°, and both had vertical gratings. Similarly, the orientation sensitivity test started with the least horizontally tilted stimuli of 19° and 20°. Which of the stimuli appeared first was determined randomly each time.

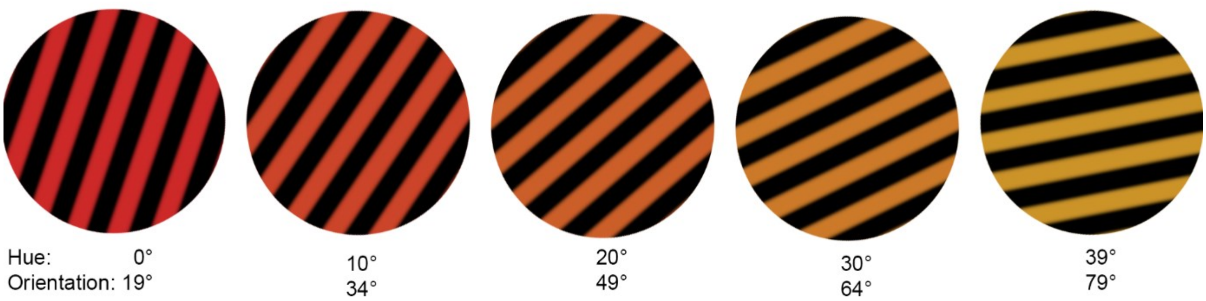

Figure 2. The minimum and the maximum values of stimuli within the colour and orientation sets with incremental intermediate values.

After being presented with the two colours the participants were asked to indicate if they were the same or not by pressing corresponding keyboard buttons (left and right arrow keys). In case a wrong answer was made, the difference between the hues of the stimuli was increased by 1°. In case the correct answer was given, the same stimuli they were presented again until four correct answers in a row were given. In such a case, both colours were added to the individual stimuli set. Subsequently, the next pair of hues were presented (e.g., 6° and 7°) and the same procedure repeated. This was repeated until the participants had distinguished between five colours. The same procedure was carried out to construct an individual list of just-distinguishable orientations.

The two individually determined lists of features were used for the second part of the experiment in which the participants' visual working memory was tested. This part consisted of three blocks, one for each of the attention instruction conditions (colour, orientation, or colour and orientation; Fig. 3). Each block began with a practice trial for the respective condition during which the participants could familiarise themselves with the task. After five trials of practice, the participants received instructions to focus on either colour, orientation, or both. The order of attentional instruction conditions presented was counterbalanced for each participant in a chronological order based on the participants' number. Each of the three blocks consisted of three sub-blocks with either one, two or four stimuli presented in one of the placeholders around the fixation cross. The order of sub-blocks was randomised. Each sub-block consisted of 60 trials, which yielded 180 trials per each condition block and 540 trials in total.

During each trial, the stimuli were constructed by randomly drawing the features from the two individual lists with replacement. Each trial began with a 1000-ms fixation cross appearance. Consequently, the stimuli were presented for 2000 msec, followed by a fixation cross for the duration of 1000 msec, after which the response screen was presented. A prompt was presented in the place of the stimuli the feature of which the participant was required to recognise. The prompt was a dark grey square with a surface of 9° × 9°. At the bottom of the screen, five gratings of a 2.3° radius with the features from the individual list were shown in ascending order with corresponding key numbers (1-5). Depending on the condition, either colours or orientations were presented. In the colour and orientation condition, the type of feature to be recalled was determined randomly for each trial. The participants were asked to press a respective keyboard key to indicate what the colour or orientation of the stimuli in the particular place had been. Consequently, the feedback was provided (correct or incorrect) and the participants had to press the spacebar to continue to the next trial. After each block, the participants had a five-minute break.

After the completion of the three blocks, the participants filled out a paper-and-pen questionnaire with their descriptive data, such as age, gender, past or current neurological disorders, and a handedness questionnaire (Annett, 1970). In total, each experiment session took about one and a half hours to complete.

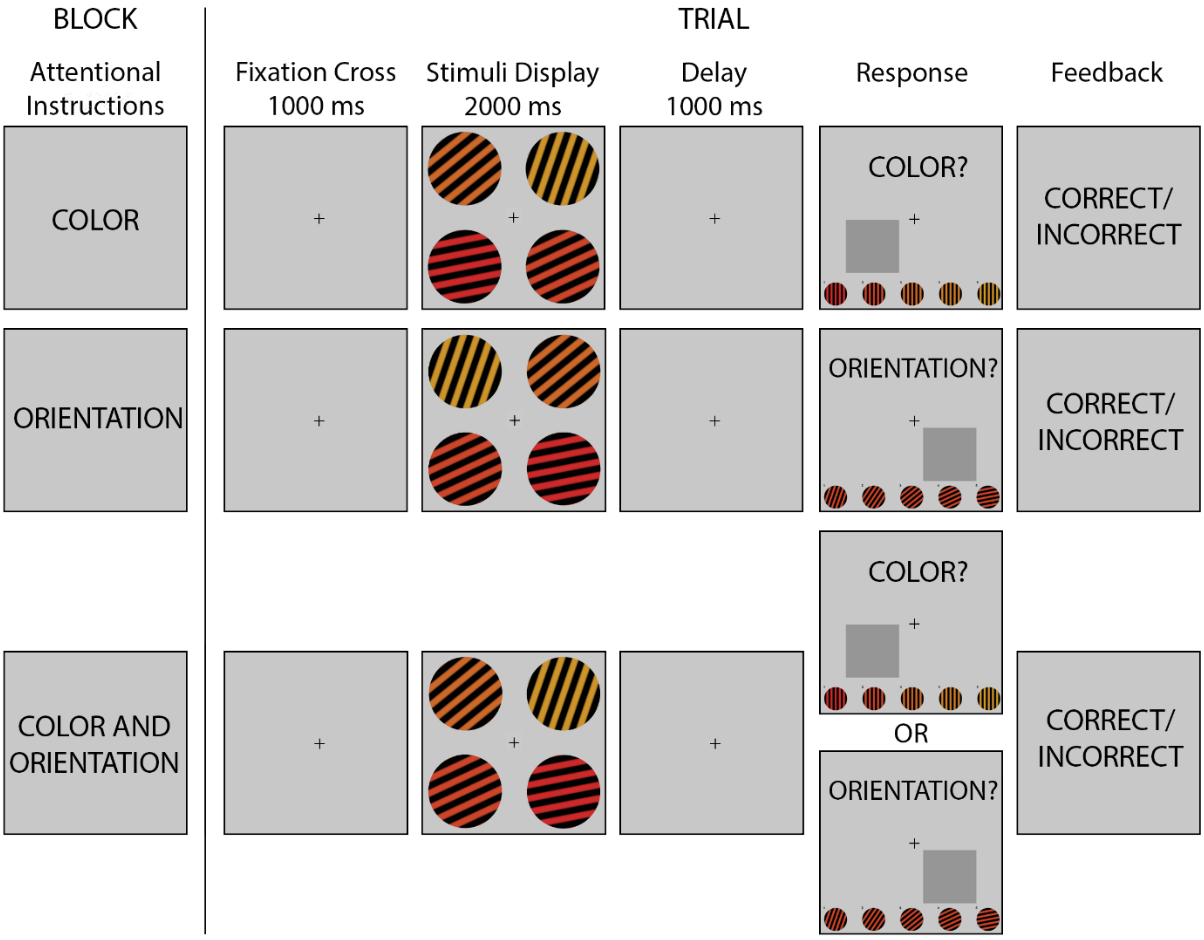

Figure 3. Visual short-term memory task (stimuli not depicted to scale). At the beginning of each block, the participants were instructed to attend to either colour, orientation, or both. Each trial began with a fixation cross, followed by one, two, or four two-feature stimuli display of 2000 msec. After a 1000-ms delay, the participants were presented with the gratings with condition-respective feature and asked to indicate which feature the stimulus in the probed area had. In the colour and orientation condition, the feature to be recalled was randomly determined on every trial.

Statistical Approaches

The data used for the analyses were tested for normality, homoscedasticity, and sphericity; no critical violations of any of the assumptions were found. In order to test whether the scale of the perceived changes in colours and orientations in the individually constructed lists of just-discriminable features is linear, a one-way repeated measures ANOVA was used for both colours and orientations sets. The independent variable was Pair of Features with four levels corresponding to each of the four consecutive pairs of features within the individually determined lists of colours and orientations. The dependent variable was the Distance between the features, measured in hue angles for colour and in rotation angles for orientation. In case the scale of perceived changes was not linear, the distances between some pairs of features were expected to be unequal to the distances between the others.

To test whether the observed accuracy performance was above chance, the mean error distances (EDs) for each condition were tested against the average distance value (=1.6), which would be observed in case participants were exhibiting guessing behaviour, using a one-sample t-test for each of the nine possible condition combinations. The average distance value was calculated by, first, determining all the possible distances from the correct answer to the observed one (varying from zero to four) for each of the five possible responses and second, by calculating the average of these distances.

To test for the effects of attentional instruction and set size, a within-subjects design was employed with two three-level independent variables: Attention Condition (Colour, Orientation, Colour and Orientation) and Number of Stimuli (1, 2, or 4). The dependent variable was the mean EDs calculated as the difference between the feature's correct number in the individual list (0-4) and guessed feature's number. In order to check for the effects of the independent variables, 3 (Condition: Colour, Orientation, Colour and Orientation) × 3 (Number of Stimuli: 1, 2, or 4) repeated measures ANOVA was used.

Results

Distances between Features within Individual Sets

The total distances between the first and the last features in the individually constructed sets of colours and orientations are shown in Figure 4. A repeated measures ANOVA design was used to analyse the differences between the pairs of features within the individual just-distinguishable feature sets for both colour and orientation. As was expected in case the scale of perceived changes in features is not linear, the effect of Pair of Features on the Distance between items was significant for the colour sets, $F(3, 51) = 10.4$, $p < 0.001$, $\eta_p^2 = 0.38$. A post hoc test with a Bonferroni correction showed that the Distance was found to be significant between the first (M = 6.28) and the second (M = 4.33) pairs of features, $p < 0.001$, $d_{avg} = 1.41$, and the first and the third (M = 4.9) pairs, $p < 0.05$, whereas the differences in Distance between first and the fourth (M = 5.2), second and the third, second and the fourth, and the third and fourth pairs was not significant, $p > 0.05$. However, Pair of Features did not have a significant effect on the Distance between items in case of the orientation sets, $F(3, 51) = 2.0$, $p = 0.123$, indicating that the shape of the scale of perceived changes in orientation does not differ from a linear one.

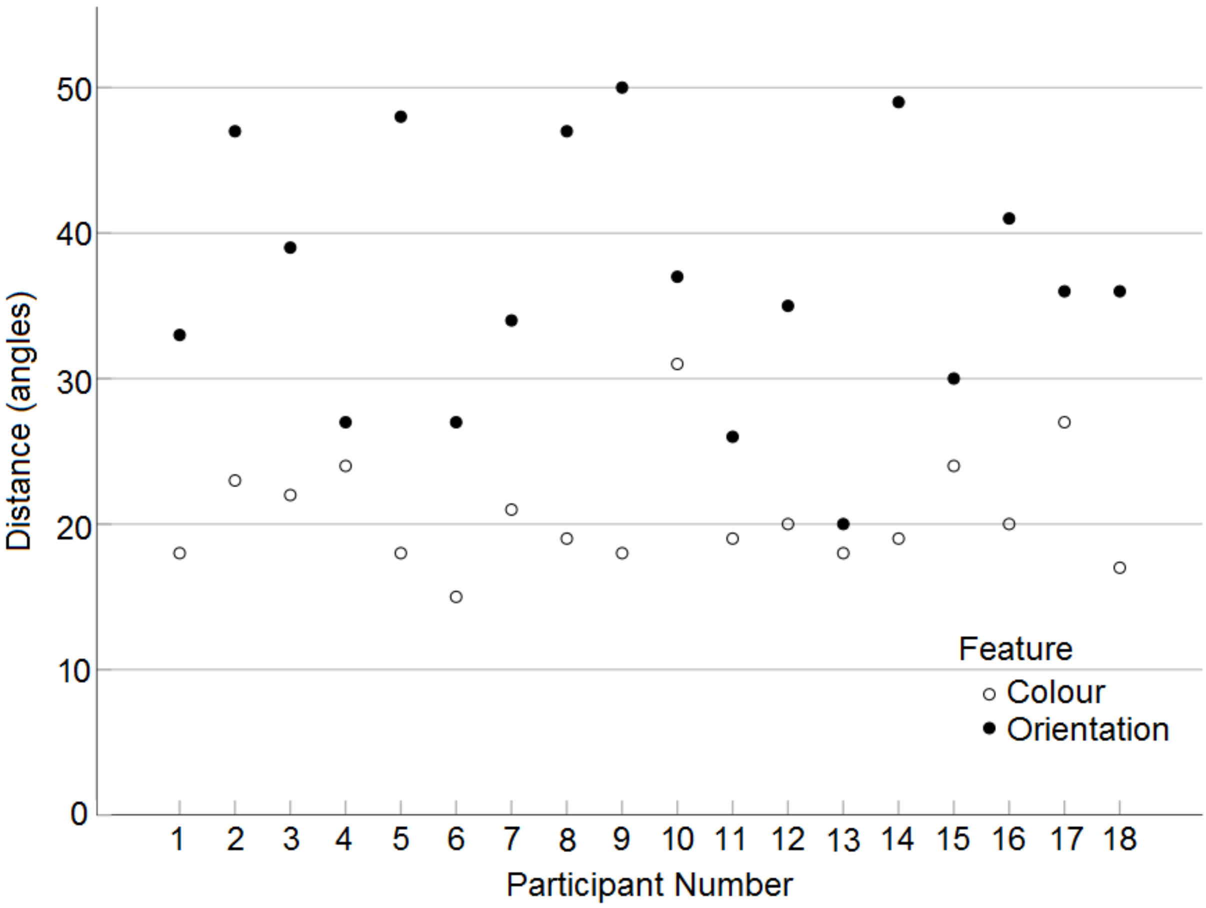

Figure 4. During the sensitivity test, each participant constructed individual sets of just-distinguishable colours and orientations. Shown in the graph are the total distance in angles between the first and the last feature in both sets.

Above-chance Performance

The results of the t-test showed that in each of the nine condition combinations the mean EDs were significantly lower than the value expected to be observed by chance, which indicated that the participants exhibited above-chance accuracy in all conditions. The largest divergence from the chance value was observed in colour condition with one stimulus, $M_{diff} = -1.27$, $t(17) = -42.9$, $p < 0.001$, $d_m = -10.12$, whereas the smallest difference was found in colour and orientation condition with four stimuli, $M_{diff} = -0.51$, $t(17) = -11.4$, $p < 0.001$, $d_m = -2.69$. Hence, it can be concluded that guessing did not prevail the performance in any of the conditions.

Visual Working Memory Task

A repeated measures ANOVA design was used to analyse the error distances, varying from a minimum of zero to a maximum of four, in different attentional instruction conditions and set sizes. As expected, it showed that the main effect of Attention Condition was significant, $F(2,34) = 56.7, p < 0.001, \eta_p^2 = 0.77$, with Colour condition having the lowest mean EDs (0.5), followed by Orientation (0.75), and Colour and Orientation (0.86). Furthermore, in line with the expectations, the Number of Stimuli had a significant effect on the mean EDs, $F(2,34) = 106.3$, $p < 0.001$, $\eta_p^2 = 0.86$. As predicted, the EDs gradually increased with an increase in the Number of Stimuli. The mean EDs observed in the single stimulus condition were 0.47, 0.73 in the two stimuli condition, and 0.9 in three stimuli condition. Importantly, the interaction between the two main effects was found to be significant, $F(4, 68) = 3.7$, $p < 0.01$, $\eta_p^2 = 0.18$. The lowest EDs were observed in the Colour condition with one stimulus (Fig. 5). The EDs significantly increased in the two-stimuli condition, $t(17) = -9.5$, $p < 0.001$, $d_{avg} = -1.63$. However, the difference in EDs between two- and four-stimuli conditions when only the colour had to be recalled was not significant, $t(17) = -1.4$, $p = 0.19$.

Compared to the Colour condition, the EDs in Orientation condition with one stimulus were significantly larger, $t(17) = -2.7$, $p < 0.05$, $d_{avg} = -0.84$. Similarly to the Colour condition, the increase in EDs between one and two stimuli conditions for Orientation was significant, $t(17) = -12.6$, $p < 0.001$, $d_{avg} = -1.64$. In contrast to the findings regarding Colour condition, the EDs increases significantly further from two- to four-stimuli condition, $t(17) = -4.3$, $p = 0.001$, $d_{avg} = -1.09$. Comparably, in the Colour and Orientation condition, the differences between the EDs in both one- and two-stimuli and two- and four-stimuli conditions were significant, $t(17) = -3.7$, $p < 0.05$, $d_{avg} = -1.03$ and $t(17) = -3.4$, $p < 0.05$, $d_{avg} = -1.08$ respectively.

Interestingly, the difference in EDs between Orientation and Colour and Orientation conditions were only significant in the one-stimulus condition, $t(17) = -3.0$, $p < 0.05$, $d_{avg} = -0.63$. The difference between the EDs of the two attention conditions was not significant in the two-stimuli condition, $t(17) = -1.5$, $p = 0.17$, nor was it significant in the four-stimuli condition, $t(17) = -1.2$, $p = 0.24$.

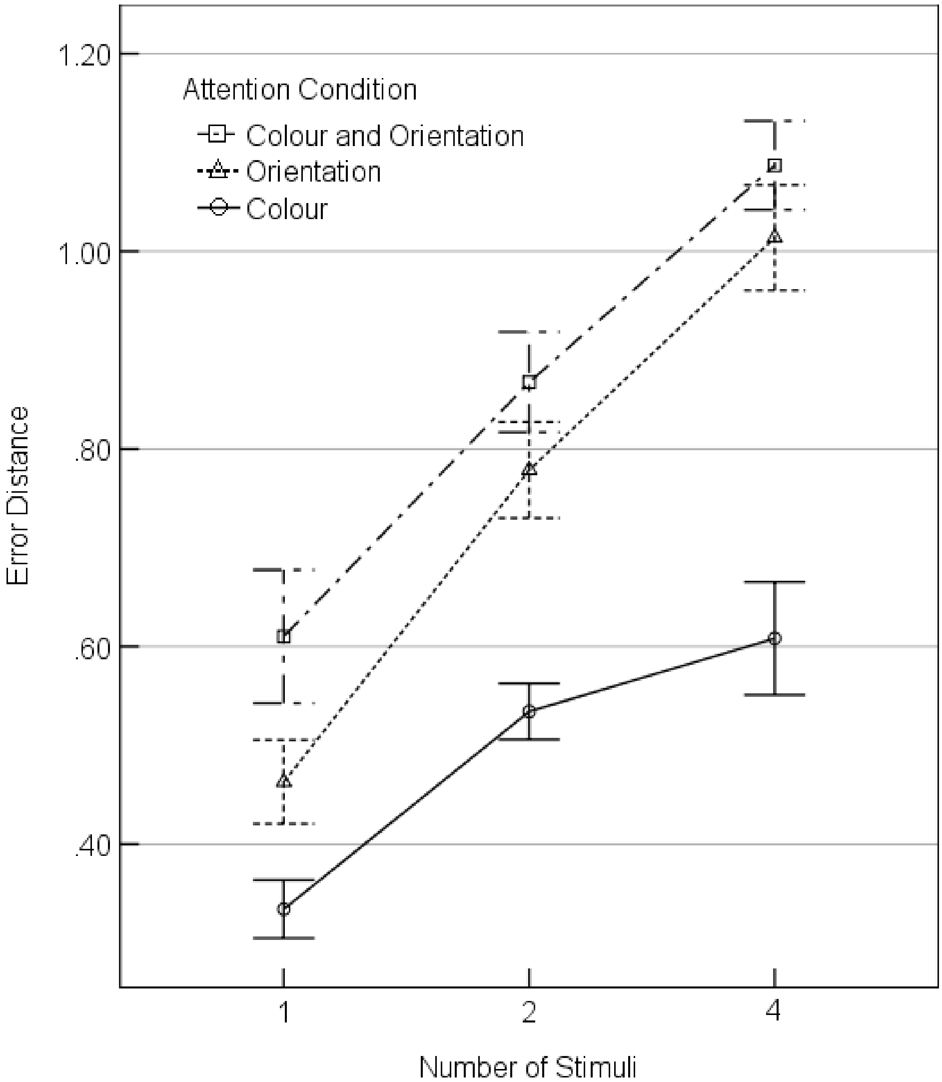

Figure 5. The mean Error Distances (0-4) as a function of the Attention Condition and the Number of Stimuli. Error bars denote ± SEM.

Discussion

The Effects of the Set Size and Feature-Selective Attention

The main aim of the present study was to examine which of the presently available conflicting theoretical models, discrete-capacity or limited-resource, is a better fit to the obtained findings. As expected, the results offer support for limited-resource models of VWM and contradict discrete-capacity models. Discrete-capacity models hold that the whole integrated objects are encoded to VWM until all available slots are filled (Cowan, 2001; Luck & Vogel, 1997). According to these models, the recall precision is expected to be similar regardless of the number of objects presented or the number of features that the objects have, as long as the capacity limit of approximately 4 objects is not exceeded (Cowan, 2001). After a capacity limit is reached, the additional objects or their features are predicted not to be encoded at all. However, the results of the current study contradict these predictions, and in accordance with the expectations based on limited-resource models, show that the variability in performance accuracy was already observed when only one stimulus was presented and continued to gradually increase when the set size was increased.

Importantly, the present results also provide significant insights for the debate regarding the units of visual attention. Underlying discrete-capacity models is the integrated object account, which suggests the units of visual attention to be unitary objects with all their features which are encoded as a coherent unit regardless whether the attention is focused on the whole object or only a certain feature (Brummerloh et al., 2019; Luck & Vogel, 1997; O'Craven, Downing, & Kanwisher, 1999; Park et al., 2017). Accordingly, the attentional instructions would not be expected to affect the accuracy of recall. However, the present results contradict such notions and indicate providing the participants with feature-selective attention instructions has a significant impact on the recall variability. The smallest recall variability was observed when only the colour of the stimuli was attended. An increase in the recall variability was only observed when comparing one- and two-stimulus conditions. However, the performance accuracy was similar when two and four stimuli had to be recalled, which suggests colour to be recalled equally well regardless of whether two or four different colours have to be memorised.

Compared to the performance in colour recall, a significant decrease in accuracy was observed when the orientation had to be recalled. The error distances were found to be higher than those in colour condition when the same number of stimuli was presented. These results cannot be explained by the integrated object account, according to which both features would have equal recall accuracy if they belong to the same object, nor can it be explained by perceptual differences between the two features, for which it was corrected using the sensitivity task. The colour and orientation conditions differed only with regard to the feature that had to be attended; this shows that feature-selective attention biases the initial encoding process by enhancing the internal representations in VWM of only the task-relevant feature (Park et al., 2017). Furthermore, in contrast to the colour condition, the recall variability in the orientation condition gradually increased with each expansion of the set size which indicates that VWM performance varies when different features have to be recalled. These findings are in line with the results of previous research in which evidence was found for the existence of separate independent capacity limits for each visual feature of the same object (Lilburn, Smith, & Sewell, 2019; Markov et al., 2019; Shin & Ma, 2017; Wang, Cao, Theeuwes, Olivers, & Wang, 2017).

The lowest recall accuracy was observed in the colour and orientation condition. When both features had to be attended, the recall variability in one-stimulus condition was higher than in isolated colour or orientation conditions. This resulted was expected based on the limited-resource feature-based views, according to which the increase in number of features to be recalled has negative effect on the recall precision. However, the recall accuracy was not significantly different from that observed in orientation condition when comparing the performance with a set size of two and four stimuli. Interestingly, in these cases, memorising the colour of the stimuli did not have an additional effect compared to that obtained when only the orientation had to be attended, which could be expected given the existence of the independent resource pools in VWM for colour and orientation (Markov et al., 2019; Shin & Ma, 2017; Wang et al., 2017). These findings conflict the postulations of discrete-capacity models by showing that the features do not have equal weights, as would be expected if they would be encoded as a part of an integrated object. However, the lack of difference between the recall precision in the orientation and colour and orientation conditions cannot be explained on the basis of limited-resource models either. According to the feature-based view, the recall precision was expected to be lower when two different features of an object had to be memorised as compared to only one feature. Nevertheless, the recall precision was different between the two orientation and colour and orientation conditions only when one stimulus was presented, and no difference was observed with two or four stimuli.

Physical versus Perceived Changes in Features

The analyses of the perceived changes in the two features provided opposing results. Whereas the scale of the perceived changes in colour significantly differed from linear, the scale of perceived changes in orientation did not. These results, however, should be interpreted with caution as the high variability in the individual ability to distinguish between orientations has a negative effect on the statistical power for the hypothesis testing. Based on these findings, the expectation for the non-linear scale of the perceived changes has been partially met which signifies the importance of a sensitivity test being included in the study design in order to correct for the non-linearity in the observed errors during the main VWM task.

Limitations and Future Directions

The results of the present study related to the recall of the colours of the stimuli may have been affected by the features of the used set. The colour set was composed by varying the hue of the colour due to which the colours in the individually constructed sets appeared to turn lighter, from dark red to orange. Consequently, the participants reported being able to internally verbalise which of the presented colours were the darkest and the lightest. In turn, this might have positively influenced the performance and decreased the difficulty in memorising the colours compared to orientations. Future research could correct for such effects by using a colour set in which the internal verbalisation of colour would be less likely, for instance, by using another colour system, such as the CIELAB colour space.

An additional possible direction for future research is the replacement of the features used in the current study or inclusion of new features, such as shape or size. This way it could be examined how different features affect the memory precision in comparison to colour and orientation. Adding new features to the task would also reveal whether having to recall more than two different features with the same number of stimuli being presented would result in comparable error distances, which would be expected under the predicted existence of independent resource pools for different features.

Conclusion

The results of the present study provide compelling evidence against discrete-capacity models under the predictions of which no difference in recall precision would have been expected to be observed between the three different attentional instruction and number of stimuli conditions. While contradicting the object-based view, the results support the feature-based view, according to which single features rather than unitary objects to be the units of

VWM. Furthermore, the findings are partially consistent with limited-resource models which predict the response errors to be present even below the item limit suggested in discrete-capacity models and to increase continuously as a function of the presented set size (Lilburn et al., 2019). Although the performance of VWM is imperfect, a flexible attention focus allows the most important features to be recalled with higher precision. However, limited-resource models do not provide a complete explanation of the present results, specifically, the absence of an expected decrease in the recall precision when both colour and orientation had to be memorised in comparison to when only the orientation had to be attended. In agreement with previous studies (e.g., see Lilburn et al., 2019; Markov et al., 2019; Shin & Ma, 2017; Wang et al., 2017), these results suggest that different features tap independent resource pools, which offers a new perspective on limited-resource models.

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