Negative Affect Improves the Quality of Memories:

Trading Capacity for Precision in Sensory and Working Memory

Philipp Spachtholz

University of Munich

Christof Kuhbandner

University of Regensburg

Reinhard Pekrun

University of Munich

Journal of Experimental Psychology: General

(in press, February 2014))

Author Note

Philipp Spachtholz, Department of Psychology, University of Munich, Munich, Germany; Christof Kuhbandner, Department of Psychology, University of Regensburg, Regensburg, Germany; Reinhard Pekrun, Department of Psychology, University of Munich, Munich, Germany.

The first two authors contributed equally to this work. We thank Dr. Kou Murayama (University of Reading, UK) for providing helpful comments on an earlier version of this article.

Correspondence concerning this article should be addressed to Philipp Spachtholz, Department of Psychology, University of Munich, 80802 Munich, Germany. E-mail: spachtholz@psy.lmu.de

Word Count: 3,618 words, *Display Items:* 2 Figures, *Reference List:* 34 Items.

Abstract

Research has shown that negative affect reduces working memory capacity. Commonly, this effect has been attributed to an allocation of resources to task-irrelevant thoughts, suggesting that negative affect has detrimental consequences for working memory performance. However, rather than simply being a detrimental effect, the affect-induced capacity reduction may reflect a trading of capacity for precision of stored representations. To test this hypothesis, we induced neutral or negative affect and concurrently measured the number and precision of representations stored in sensory and working memory. As compared with neutral affect, negative affect reduced the capacity of both sensory and working memory. However, in both memory systems, this decrease in capacity was accompanied by an increase in precision. These findings demonstrate that observers unintentionally trade capacity for precision as a function of affective state and indicate that negative affect can be beneficial for the quality of memories.

Keywords: emotions, short-term memory, iconic memory, emotional states, stimulus salience

Negative Affect Improves the Quality of Memories: Trading Capacity for Precision in Sensory and Working Memory

Working memory (WM), a system allowing us to temporarily maintain information, plays a major role as an interface between sensory memory (SM), long-term memory, and behavior (Shiffrin & Atkinson, 1969). However, unlike SM and long-term memory, WM is known to be severely limited in capacity because only a small amount of information can be stored simultaneously (Cowan, 2001). WM capacity varies between individuals (Vogel & Machizawa, 2004), and its importance is underlined by its positive correlations with variables of cognitive performance such as fluid intelligence (Fukuda, Vogel, Mayr, & Awh, 2010) and academic achievement (Alloway & Alloway, 2010).

Previous research has shown that WM capacity can vary depending on state factors. One state factor that has been the focus of considerable research is affective state, with the general finding that negative affect reduces WM capacity (Ellis & Ashbrook, 1988; Meinhardt & Pekrun, 2003). For instance, using the classical capacity measures of memory and reading span, Spies, Hesse, and Hummitzsch (1996) have shown that experimentally induced negative affect reduces WM capacity. Furthermore, a recent study demonstrates that such effects are also observed in real life. Using a 3-back WM task, Brose, Schmiedek, Lövén, and Lindenberger (2012) observed that daily fluctuations in negative affect are coupled with daily fluctuations in WM performance. Such detrimental effects of negative affect have been commonly attributed to two different sources. First, when negative affect is experienced, the emotion itself may capture attention so that the amount of resources available for the task at hand is reduced (Ellis & Ashbrook, 1988; Wine, 1971). Second, experiencing negative affect may decrease task motivation so that fewer resources are allocated to the task at hand (Hertel & Rude, 1991; Pekrun, 1992, 2006).

However, there may be an alternative explanation for the affect-induced decrease in WM capacity. From a functional point of view, affective states reflect the requirements of the current situation which have to be met for optimal functioning (Frijda, 1988). As negative affect typically signals a problematic situation, a careful assessment of the situation with close attention to the details would be adaptive (Schwarz, 2002). Thus, the optimal processing style would be to represent incoming information with greater quality and precision. However, due to resource limitations of WM, such an increase in precision may come at the cost of a decrease in the number of representations that can be stored. Accordingly, the reduced WM capacity found in negative states may reflect a trading of quantity for quality rather than a true capacity deficit, suggesting that the effect of negative affect can be functional rather than detrimental.

Previous studies on the influence of affect on WM capacity cannot rule out this possibility because only quantity but not quality of representations has been measured. However, recently, WM research has developed a paradigm to concurrently measure both the number and precision of stored representations, showing that observers can indeed trade between quantity and quality, although there seem to be upper limits for both capacity and precision (e.g., Zhang & Luck, 2008; 2011). Using this paradigm, the present study examined whether the affect-induced reduction in WM capacity reflects a true capacity deficit or rather a trade-off between quantity and quality. To examine the role of affect, we induced neutral or negative affect using a standard affect-induction procedure involving music and guided rumination. As there is evidence that the trading between quantity and quality is less limited at earlier processing stages (Zhang & Luck, 2011), we measured the effect of negative affect on the quantity and quality of stored representations both in WM and SM. We expected to replicate the typical finding of an affect-induced reduction in the number of representations that can be stored in WM, and we speculated that a similar effect would be present in SM, although evidence on this issue is lacking. However, if the reduction in capacity in negative states reflects a trade-off between quantity and quality, then the decrease in the number of stored representations should come along with an increase in the precision of stored representations in both memory systems.

Method

Participants and Design

Eighty undergraduate students (65 females, mean age = 24.4 years, *SD* = 7.1) participated for course credit. All participants provided written informed consent and reported normal color vision and normal or corrected-to-normal vision acuity. Half of the participants were randomly assigned to a neutral affect condition, the other half to a negative affect condition. In each affect condition, participants performed a SM and a WM task.

Material

Stimuli were presented on an LCD monitor, calibrated with an X-Rite i1 Pro colorimeter, on a gray background (27.1 cd/m^2) at a viewing distance of 50 cm. The stimulus material consisted of a set of colored squares (2° x 2°) which were placed in one of eight possible equidistant locations along an invisible circle (4.5° radius). The colors of the squares were drawn from a master set of 180 colors which was constructed by choosing evenly distributed equiluminant colors from a circle in the CIE L*a*b* color space (center: L* = 70, a* = 0, b* = 0; radius: 43). Selection from this master set was random with the restriction that the minimum angular distance between two colors was 24° to ensure discriminability. For response collection, the squares were surrounded by a color wheel (8.2° radius, 2.2° thickness) consisting of all 180 colors (see Figure 1A).

Procedure

Each trial started with the presentation of a sample array for 200 ms consisting of either four (WM task) or, in order to avoid ceiling effects, six (SM task) colored squares (see Zhang & Luck, 2011). The sample array was followed by a blank screen. As information stored in visual SM decays after about 300 to 500 ms (Gegenfurtner & Sperling, 1993), the blank interval was shown for 100 ms in the SM task and 1,000 ms in the WM task (e.g., Kuhbandner, Spitzer, & Pekrun, 2011). Afterwards, the test array appeared which contained an arrow pointing randomly towards the location of a to-be-reported square. Each location was cued equally often. Participants had to indicate the color of the target by clicking on the corresponding color on the color wheel. The color wheel was rotated randomly and was presented both in the sample and the test array in order to reduce masking effects. There was no time limit for responding and no feedback.

Participants initially practiced both the SM and WM task with feedback about the correct color until they responded on at least eight out of 24 trials within 60° of the target color. After practice, affect was induced. Participants recalled a neutral or sad autobiographical event for three minutes while listening to appropriate music (Negative: “Adagio in G Minor” by Albinoni, see Jefferies, Smilek, Eich, & Enns, 2008; Neutral: “Overture for trumpet & orchestra in C Major” by Ludwig Güttler & Virtuosi Saxoniae). Music continued to play softly throughout the remainder of the experiment (see Jefferies et al., 2008). Immediately after affect induction, participants started with the memory tasks. They completed six blocks (16 trials each) of both the SM and WM task. Half of the participants started with the SM task, the other half with the WM task; memory tasks alternated across blocks. Finally, the success of affect induction was measured using the affect grid (Russel, Weiss, & Mendelsohn, 1989) which assesses affect on the dimensions of valence (1 = *extremely negative*, 9 = *extremely positive*) and arousal (1 = *low* *arousal*, 9 = *high arousal*).

Data analysis

To determine capacity and precision, we followed the steps established in previous research (Zhang & Luck, 2008). Basically, deviations from the correct color reflect a mixture of trials where the probed square was remembered and trials where observers guessed randomly. Accordingly, the distribution of errors consists of a mixture of a normal distribution (around the correct color) and a uniform distribution (random guesses). The height of the uniform portion can be used to estimate the number of stored representations, and the standard deviation of the normally distributed portion can be used to estimate the precision of stored representations.

To estimate capacity and precision, we first calculated the angular distance between the correct and the reported color which represents the degree of error in the reported color. We then fitted a mixture model to the error data consisting of a combination of a uniform distribution and a von Mises distribution (i.e., the circular equivalent of the Gaussian distribution). The mixture model is characterized by two parameters, *G* and *SD*. Parameter *G* reflects the height of the uniform distribution and represents the guessing probability, which can be used to calculate the probability (*PM*) that the probed item was present in memory (*PM* = 1 - *G*). Memory capacity (K) can then be calculated by multiplying *PM* by set size. Parameter *SD* reflects the standard deviation of the von Mises distribution and represents the width of the distribution of response errors on trials where the probed item was present in memory. As *SD* is inversely related to the precision of stored representations, precision can be characterized by the reciprocal of SD (i.e., SD^{-1}; Bays & Husain, 2008). The mixture model was fitted to the error data in each experimental condition using maximum-likelihood estimation (Myung, 2003).[1] To compare parameter estimates, z-tests were performed by obtaining asymptotic standard errors from the

Hessian matrix of second partial derivatives (Rohrer & Wixted, 1994).

Results

Affect Manipulation

Two participants were excluded, one because of a computer failure, one because of failure to reach the accuracy criterion in the practice phase. Participants varied reliably in their affective ratings across affect conditions. As compared to the neutral condition (valence: M = 6.4, SD = 1.8; arousal: M = 5.6, SD = 1.7), participants in the negative condition rated lower on the valence dimension (M = 3.4, SD = 1.4), $t(76) = -8.17$, $p < .001$, d = 1.86, and lower on the arousal dimension (M = 3.7, SD = 1.9), $t(76) = -4.59$, $p < .001$, d = 1.05.

Memory Performance

The mixture model fitted the data generally very well (SM: adjusted $R^2_{neutral} = .96$, adjusted $R^2_{negative} = .98$; WM: adjusted $R^2_{neutral} = .99$, adjusted $R^2_{negative} = .99$). Figure 1B shows the best fitting parameters K (i.e., capacity; left panel) and SD^{-1} (i.e., precision; right panel) for each experimental condition. Parameter K was decreased for the negative compared to the neutral condition, both for the SM task, $z = -4.45$, $p < .001$, and the WM task, $z = -2.35$, $p = .019$, indicating that negative affect decreased the capacity of both SM and WM. By contrast, parameter SD^{-1} was increased for the negative compared to the neutral affect condition, both for the SM, $z = 2.93$, $p = .003$, and the WM task, $z = 2.45$, $p = .014$, indicating that negative affect increased the precision of stored representations both in SM and WM. Comparing the size of the effect of affect between SM and WM revealed that the effect on capacity was stronger in SM than in WM, $z = 2.54$, $p = .011$, whereas the effect on precision did not differ between SM and WM, $z = -1.01$, $p = .309$.[2]

As outlined in several theories of visual perception (e.g., Itti & Koch, 2001; Wolfe, 1994), the responding to objects in the environment is not only determined by the internal state of the observer (i.e., top-down), but also by external stimulus characteristics such as salience (i.e., bottom-up). In line with these theories, recent research has shown that an incoming stimulus is not only stored more precisely if the observer's cognitive system is tuned towards precision, but also if the stimulus is salient (Bays & Husain, 2008). Accordingly, it may be that affective effects on an observer's capacity-precision trade-off are stronger for non-salient stimuli because salient stimuli are processed highly precisely via bottom-up processes independently of current affect. To examine this issue, we rotated a segment containing 45 colors around the color wheel (see Figure 2A) and fitted the mixture model to the respective subsets (i.e., we fitted the model to the subset of colors 1 through 45, then to the subset of colors 2 through 46, and so on).[3]

Figure 2B shows the best fitting parameters K and SD^{-1} for each color subset as a function of affect condition. There was indeed a range of colors that were more preferentially stored with high precision, independently of affect. Interestingly, the colors in that range were near the chromatic loci of human lips and skin (Gozalo-Diaz, Lindsey, Johnston, & Wee, 2007), and there is indeed evidence that such colors are more salient (Lindsey et al., 2010). As shown in Figure 2C, when analyzing our data only for salient targets,[4] no effects of affect were observed, neither in SM nor in WM (capacity: $z < 0.50$, $p > .622$; precision: $z < 0.71$, $p > .481$). By contrast, for non-salient targets, strong effects of affective state were observed, both in SM (capacity: $z = -5.21$, $p < .001$; precision: $z = 3.03$, $p = .002$) and WM (capacity: $z = -2.64$, $p = .008$; precision: $z = 2.01$, $p = .044$).

According to the affective ratings, participants in the neutral and negative conditions differed not only in valence but also in arousal. Thus, the question arises whether the observed effects are driven by valence or arousal. Correlating the parameter estimates (pooled across SM and WM) for capacity and precision fitted for each individual (see footnote 2) with the valence and arousal ratings revealed that capacity increased and precision decreased from negative to neutral affect, $r = .28$, $p = .026$, and $r = -.36$, $p = .003$, respectively. By contrast, both precision and capacity were unrelated to arousal levels, *r*s < .18, *p*s > .176. These findings suggest that the observed effects were driven by valence rather than arousal. However, given that the individual fits were based only on 96 trials per condition, further research is needed to confirm this finding.

Discussion

The present results replicate previous findings showing that negative affect reduces WM capacity (e.g., Spies et al., 1996). Going beyond previous findings, our results demonstrate that an affect-induced capacity reduction is already found in SM. However, most intriguingly, both in SM and WM the affect-induced capacity decrease was accompanied by an increase in precision of stored representations, indicating that negative affect can bring about a trading of quantity for quality. As negative affect typically signals that a situation is problematic, such a processing style may be optimal to meet situational requirements because incoming information is represented with greater precision. More generally, these findings contribute to the growing body of evidence showing that negative affect need not be detrimental for the quality of cognitive performance (e.g., Kuhbandner et al., 2009; Pekrun, 2006; Storbeck & Clore, 2005; see Forgas, 2013, for a review), suggesting that the effects of negative affect can be functional rather than detrimental.

An interesting finding was that effects of affective state were only observed for non-salient but not for salient targets because salient targets were generally preferentially processed with high precision, independently of affective state. This finding replicates recent findings that salient stimuli are stored more precisely than non-salient stimuli (Bays & Husain, 2008), and demonstrates that such effects are also found in the domain of color. Going beyond previous findings, our results indicate that the precision with which incoming stimuli are stored is determined by the interplay between the precision adjustment of the observer's cognitive system and stimulus salience. This is in line with current theories of visual processing (e.g., Itti & Koch, 2001; Wolfe, 1994) postulating that the responding to objects in the environment is a function of both the internal state of the observer (i.e., top-down) and external characteristics of the objects (i.e., bottom-up). Critically, bottom-up effects on the precision of stored representations may represent an important confound in previous studies examining the effects of different internal states on the trade-off between capacity and precision (e.g., motivational states; Zhang & Luck, 2011). As these studies did not control for potential effects of stimulus salience, bottom-up driven salience effects may have clouded actual differences between conditions.

The present results are well in line with slots-models of WM, assuming that WM consists of a limited number of slots with a fixed-resolution (Zhang & Luck, 2008). First, the size of the precision increase in WM in the negative condition is as expected by slots models. Slots models suppose that precision can be increased by storing independent samples of the same stimulus in different slots, and then reporting the average of the stored samples. Accordingly, the achieved precision should be equal to the precision of a single slot multiplied by the square root of the number of slots devoted to the stimulus (Zhang & Luck, 2008). In our study, negative affect decreased WM capacity by 0.24, which can be interpreted as if on average on 24 % of the trials one slot was additionally devoted to the same stimulus. Assuming that SD in the neutral condition (0.035 deg^{-1}) resembles the precision of one slot, slots-models would predict a mean precision of 0.039 deg^{-1} in the negative condition, which corresponded well with the observed precision (0.040 deg^{-1}). Second, slots models suppose that incoming information can only be represented in WM within the current precision limits of WM. Because an item has to be transferred from SM to WM in order to be reported, this may explain the finding that the size of the precision increase brought about by negative affect was similar in the SM and WM conditions, although the affect-induced trading of capacity seemed to be stronger in the SM than the WM conditions.

WM is typically divided into two separate subsystems for verbal and visual information (e.g., Baddeley, 1986), and an affect-induced capacity reduction has been found in both subsystems (e.g., Spies et al., 1996; Brose et al., 2012). As the present study examined the effects of affect on visual WM, it remains to be shown whether the affect-induced reduction of verbal WM capacity reflects a trading of quantity for quality as well. This question is difficult to examine, however, because the psychometric estimation of the trade-off between quantity and quality has been established only for visual WM but not for verbal WM. Nevertheless, given that the previously suggested mechanism to explain the effect of affect on capacity in terms of distraction by task-irrelevant thoughts may be more pertinent to the verbal than the visual domain, it may be that an affect-induced capacity reduction of verbal WM more likely reflects a true capacity deficit, and thus a detrimental effect.

In conclusion, the present findings demonstrate that both in SM and WM a trading of capacity for precision can be brought about unintentionally by cues such as affective state that signal the requirements of the current situation. Thus, other than previously thought, the reduction of WM capacity in negative affective states seems not to reflect a detrimental effect, but a functional effect instead that allows to process information in problematic situations with high precision.

References

Alloway, T. P., & Alloway, R. G. (2010). Investigating the predictive roles of working memory and IQ in academic attainment. *Journal of Experimental Child Psychology*, *106*, 20-29. doi:10.1016/j.jecp.2009.11.003

Baddeley, A. D. (1986). *Working memory*. Oxford: Clarendon Press.

Bays, P. M., & Husain, M. (2008). Dynamic shifts of limited working memory resources in human vision. *Science, 321*, 851-854. doi: 10.1126/science.1158023

Brose, A., Schmiedek, F., Lövdén, M., & Lindenberger, U. (2012). Daily variability in working memory is coupled with negative affect: The role of attention and motivation. *Emotion*, *12*, 605-617. doi:10.1037/a0024436

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, *24*, 87-185. doi:10.1017/S0140525X01003922

Ellis, H. C., & Ashbrook, P. W. (1988). Resouce allocation model of the effects of depressed mood states on memory. In K. Fiedler & J. Forgas (Eds.), *Affect, cognition, and social behaviour* (pp. 25–32). Toronto: Hogrefe.

Forgas, J. (2013). Don’t Worry, Be Sad! On the Cognitive, Motivational, and Interpersonal Benefits of Negative Mood. *Current Directions in Psychological Science, 22*, 225-232. doi:10.1177/0963721412474458

Frijda, N. H. (1988). The laws of emotion. *American Psychologist*, *43*, 349-358. doi:10.1037/0003-066X.43.5.349

Frost , R. O. & Green & M. L. (1982). Velten mood induction procedure effects: Duration and postexperimental removal. *Personality and Social Psychology Bulletin* , *8*, 341-347.

doi:10.1177/0146167282082024

Fukuda, K., Vogel, E., Mayr, U., & Awh, E. (2010). Quantity, not quality: The relationship between fluid intelligence and working memory capacity. *Psychonomic Bulletin & Review*, *17*, 673-679. doi:10.3758/17.5.673

Gegenfurtner, K. R., & Sperling, G. (1993). Information transfer in iconic memory experiments. *Journal of Experimental Psychology: Human Perception and Performance, 19*, 845-866. doi:10.1037/0096-1523.19.4.845

Gorgoraptis , N., Catalao, R. F., Bays, P. M., & Husain, M. (2011). Dynamic updating of working memory resources for visual objects. *The Journal of Neuroscience, 31*, 8502-8511. doi:0.1523/JNEUROSCI.0208-11.20

Gozalo-Diaz, D., Lindsey, D. T., Johnston, W. M., & Wee, A. G. (2007). Measurement of color for craniofacial structures using a 45/0-degree optical configuration. *Journal of Prosthetic Dentistry, 97*, 45-53. doi: 10.1016/j.prosdent.2006.10.013

Hertel, P. T., & Rude, S. S. (1991). Depressive deficits in memory: Focusing attention improves subsequent recall. *Journal of Experimental Psychology: General*, *120*, 301-309. doi:10.1037/0096-3445.120.3.301

Itti, L., & Koch, C. (2001). Computational Modelling of Visual Attention. *Nature Reviews Neuroscience*, *2*, 194-203. doi:10.1038/35058500

Jefferies, L. N., Smilek, D., Eich, E., & Enns, J. T. (2008). Emotional valence and arousal interact in attentional control. *Psychological Science*, *19*, 290-295, doi:10.1111/j.1467-9280.2008.02082.x.

Kuhbandner, C., Hanslmayr, S., Maier, M. A., Pekrun, R., Spitzer, B. J., Pastötter, B., & Bäuml, K.-H. (2009). Effects of mood on the speed of conscious perception: Behavioral and electrophysiological evidence. *Social Cognitive and Affective Neuroscience, 4,* 286-293. doi:10.1093/scan/nsp010

Kuhbandner, C., Spitzer, B., & Pekrun, R. (2011). Read-out of emotional information from iconic memory: The longevity of threatening stimuli. *Psychological Science, 22,* 695-100. doi:10.1177/0956797611406445

Lindsey, D.T., Brown, A. M., Reijnen, E., Rich, A. N., Kuzmova, Y. I., & Wolfe, J. M. (2010). Color Channels, Not Color Appearance or Color Categories, Guide Visual Search for Desaturated Color Targets. *Psychological Science, 21,* 1208-1214. doi: 10.1177/0956797610379861

Meinhardt, J., & Pekrun, R. (2003). Attentional resource allocation to emotional events: An ERP study. *Cognition and Emotion*, *17*, 477-500. doi:10.1080/02699930244000039

Myung, I. J. (2003). Tutorial on maximum likelihood estimation. *Journal of Mathematical Psychology*, *47,* 90-100. doi:10.1016/S0022-2496(02)00028-7

Pekrun, R. (1992). The impact of emotions on learning and achievement: Towards a theory of cognitive/motivational mediators. *Applied Psychology: An International Review*, *41*, 359-376. doi:10.1111/j.1464-0597.1992.tb00712.x

Pekrun, R. (2006). The control-value theory of achievement emotions: Assumptions, corollaries, and implications for educational research and practice. *Educational Psychology Review*, *18,* 315-341. doi:10.1007/s10648-006-9029-9

Rohrer, D., & Wixted, J. T. (1994). An analysis of latency and interresponse time in free recall. M*emory & Cognition*, *22*, 511-524. doi:10.3758/BF03198390

Russell, J. A., Weiss, A., & Mendelsohn, G. A. (1989). Affect Grid: A single-item scale of pleasure and arousal. *Journal of Personality and Social Psychology*, *57*, 493-502.

doi:10.1037/0022-3514.57.3.493

Schwarz, N. (2002). Situated cognition and the wisdom of feelings: Cognitive tuning. In L. Feldman Barrett & P. Salovey (Eds.), *The wisdom in feelings* (pp. 144-166). New York: Guilford.

Shiffrin, R. M., & Atkinson, R. C. (1969). Storage and retrieval processes in long-term memory. *Psychological Review*, *76*, 179-193. doi:10.1037/h0027277

Spies, K., Hesse, F., & Hummitzsch, C. (1996). Mood and capacity in Baddeley's model of human memory. *Zeitschrift für Psychologie mit Zeitschrift für angewandte Psychologie*, *204*, 367-381.

Storbeck, J., & Clore, G. L. (2005). With Sadness Comes Accuracy; With Happiness, False Memory: Mood and the False Memory Effect. *Psychological Science*, *16*, 785-791. doi:10.1111/j.1467-9280.2005.01615.x

Vogel, E., & Machizawa, M. (2004). Neural activity predicts individual differences in visual working memory capacity. *Nature*, *428*, 748-751. doi:10.1038/nature02447

Wine, J. D. (1971). Test anxiety and the direction of attention. *Psychological Bulletin*, *76*, 92-104. doi:10.1037/h0031332

Wolfe, J. M. (1994). Guided Search 2.0: A Revised Model of Visual Search. *Psychonomic Bulletin & Review*, 1, 202-238. doi:10.3758/BF03200774

Zhang, W., & Luck, S. J. (2008). Discrete fixed-resolution representations in visual working memory. *Nature*, *453*, 233-235. doi:10.1038/nature06860

Zhang, W., & Luck, S. J. (2011). The number and quality of representations in working memory. *Psychological Science*, *22*, 1434-1441. doi:10.1177/0956797611417006

Footnotes

[1] Because induced affect typically fades relatively quickly (e.g., Frost & Green, 1982), we decided to collect only a limited number of trials per participant and to fit the data using aggregate data, which is recommended when there are relatively few trials per subject (Zhang & Luck, 2008).

[2] We additionally estimated the parameters using individual-subject data. Although 96 trials per condition are at the lower threshold for fitting data on an individual level, significant effects should nevertheless be observed if effects are strong enough. Indeed, the analysis exactly replicated the results obtained using aggregate data. For capacity, a 2 (affect) by 2 (memory task) mixed ANOVA revealed a main effect of affect, $F(1, 76) = 6.42$, $p = .013$, $\eta_p^2 = .08$, and a significant interaction, $F(1, 76) = 4.32$, $p = .041$, $\eta_p^2 = .05$, with the effect of affect being stronger in the SM condition ($d = 0.59$) than the WM condition ($d = 0.37$). For precision, the same ANOVA revealed a significant main effect of affect, $F(1, 76) = 6.22$, $p = .015$, $\eta_p^2 = .08$, but no significant interaction, $p = .732$.

[3] We additionally analyzed our data using a number of differently sized color segments (i.e., 15 and 30). All of the analyses showed the same pattern of results.

[4] Saliency was defined by determining the color subset with the highest combined rank of capacity and precision separately for each experimental condition. The logic behind this strategy was that previous research has shown that salient stimuli are both preferentially stored and stored with high precision (Bays & Husain, 2008; Gorgoraptis, Catalao, Bays, & Husain, 2011). The four obtained values fell into a narrow range on the color circle (eight colors), and together they defined a subset of 53 colors, which we defined as ‘salient’.

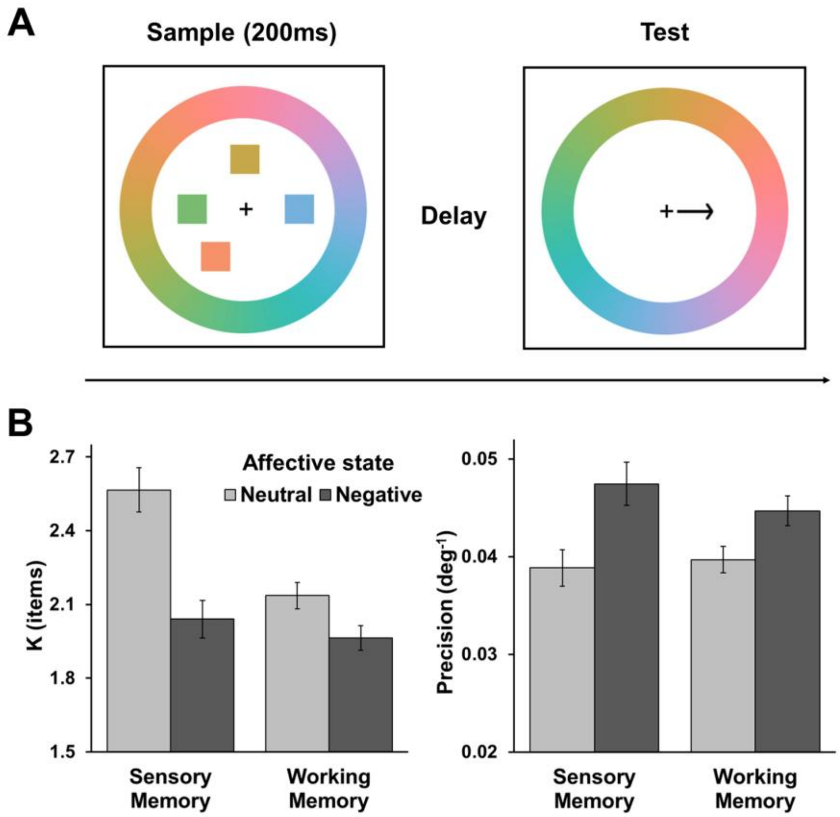

Figure 1. Procedure and results of the experiment. (A) An example of an experimental trial is shown. A circular array of four (working memory task) or six (sensory memory task) colored squares was presented for 200 ms. After a blank delay interval of 100 ms (sensory memory task) or 1,000 ms (working memory task), an arrow appeared that pointed to the target location. Participants had to report the color of the cued square by clicking on the corresponding color on the color wheel. The bar graphs in (B) show the number of items stored in memory (*K*; left panel) and the precision (SD^{-1} right panel) of the stored representations for the sensory memory and the working memory tasks as a function of affective state (neutral, negative). Error bars represent asymptotic standard errors for the parameter estimates.

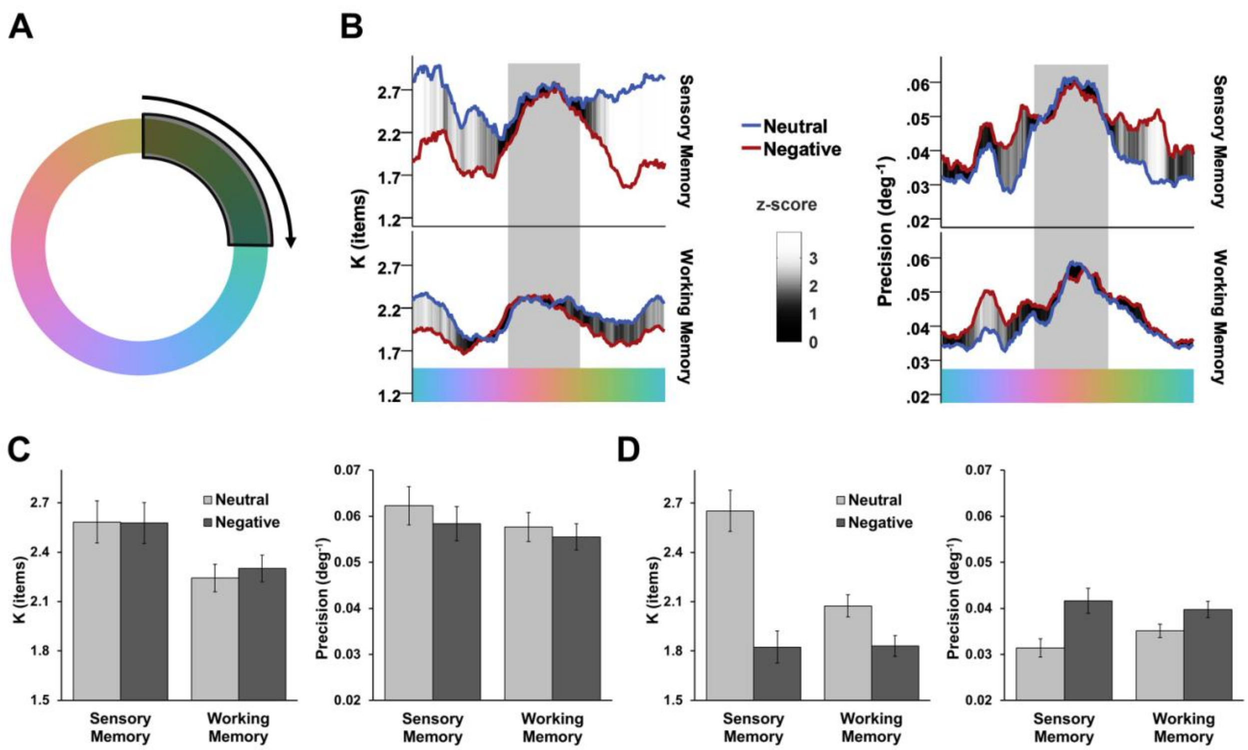

Figure 2. Role of Stimulus Salience. (A) To examine the role of stimulus salience, a segment of 45 colors was rotated around the color wheel color-by-color, and capacity and precision were estimated for each of the color subsets. (B) Capacity (left panels) and precision (right panels) estimates for each color segment are shown for the sensory and the working memory tasks as a function of affective state (neutral, negative). Z-tests were performed to compare emotional conditions for each color segment, light colors indicate high z-scores, and dark colors indicate low z-scores. The gray-shaded area indicates the subset of colors defined as salient. The bar graphs in (C) and (D) show capacity and precision estimates separately for targets colored in salient (C) and non-salient (D) colors in the sensory and the working memory conditions as a function of affective state (neutral, negative). Error bars represent asymptotic standard errors for the parameter estimates.