Cognitive constraints increase estimation biases: Cognitive load and delay in judgments

Sarah Allred and L. Elizabeth Crawford and Sean Duffy and John Smith

30. August 2014

[WORD COUNT: 4000]

Cognitive constraints increase estimation biases:

Cognitive load and delay in judgments*

Sarah R. Allred

Rutgers – Camden, Department of Psychology

L. Elizabeth Crawford

The University of Richmond, Department of Psychology

Sean Duffy

Rutgers – Camden, Department of Psychology

John Smith

Rutgers – Camden, Department of Economics

Address correspondence to:

Sean Duffy
Department of Psychology
Rutgers University, Camden Campus
343 Armitage Hall
511 N. 5th Street
Camden, NJ 08102
seduffy@scarletmail.rutgers.edu

---

*We would like to thank Roberto Barbera and Alexandra O'Donnell for help collecting data. This project was supported by Rutgers Research Council Grant # 202110 and NSF CAREER BCS 0954749. All authors contributed equally to this work.

ABSTRACT

Previous work has demonstrated that memory for simple stimuli can be biased by information about the category of which the stimulus is a member. These biases have been interpreted as optimally integrating noisy sensory information with category information. A separate literature has demonstrated that cognitive load can lead to biases in social cognition. Here we link the two, asking whether delay (Experiment 1) and cognitive load (Experiment 2) affect the extent to which observers' memories for simple line stimuli are affected by category information. We found that delay and cognitive load have similar effects: both manipulations increase the weight of category information on memory for stimuli. We discuss the broad implications of such findings on fields such as eyewitness testimony.

Cognitive Load Increases Bias in Estimation

Memory is essential for guiding behavior, yet a large body of research suggests that memory exhibits systematic biases. One well-known bias is central tendency, where individuals remember stimuli as being more typical of the category of which they are members than they actually are (Hollingworth, 1911). Once considered a perceptual or mnemonic distortion, this bias has been reinterpreted as resulting from an adaptive, Bayesian process that reconstructs inexact memories by combining them with prior knowledge about categories (Huttenlocher, Hedges, & Vevea, 2001).

Individuals may have their cognitive resources strained when remembering. For example, someone recalling a grandchild's size may be distracted by conversation. In other disciplines, such competing demands have been studied under the rubric of cognitive load. Although cognitive load clearly affects complex decision-making, little work has examined how such cognitive constraints affect memory for basic sensory information. Here we examine the how cognitive load interacts with the central tendency bias in line length estimation.

Huttenlocher and colleagues (Crawford, Huttenlocher, & Engebretson 1999; Duffy, Huttenlocher, & Crawford, 2007; Duffy, Huttenlocher, Hedges, & Crawford, 2008) have explained this bias as resulting from an adaptive process that increases the net accuracy of stimulus estimation. In their category adjustment model (CAM), a category is represented as a distribution of stimulus values along some dimension, such as size or shape, and a stimulus as a fine-grain value along the relevant set of dimensions. Categories typically have lower and upper boundaries that represent the smallest or largest possible stimulus size (i.e., the smallest and tallest tree), with the center of the category being the most typical member. For most categories, this is the running average value of the category (Duffy & Crawford, 2010). Stimuli are encoded as a fine-grain memory along the relevant stimulus dimension with some degree of uncertainty (x is *about* 35 feet tall), and as a member of a category (x is a tree). Upon recall, information from both levels is combined in a Bayesian manner to create an estimate of the stimulus, with the category information serving as the prior distribution used to adjust for the inexactness of the fine-grain memory. The CAM proposed by Huttenlocher and colleagues in similar in spirit to the Bayesian models that have been used to explain biases in memory for size estimation (Ashourian and Lowenstien, 2011), time perception (Jazayeri and Shadlen, 2010) and hue bias (Olkkonen and Allred, 2014).

Because individuals have divergent experiences with trees and other natural categories, experimental studies in the laboratory explore the central tendency bias by having people inductively learn a new, artificial category of stimuli through a task employing serial reproduction. Most commonly, lines that vary in length are used. In a canonical version of the task, participants see a study line briefly. After a delay, participants adjust a test line to match the study line. Participants repeat this process with lines that differ in size. The statistical distribution of the study line lengths quickly begins to affect behavior. Participants show a central tendency bias in their test adjustments, overestimating shorter lines and underestimating longer lines.

Bayesian models of such central tendency biases in both line length estimation and other domains predicts that increasing uncertainty of the fine grain (sensory) information will lead to greater weighting of category (prior) information, thus leading to more pronounced bias toward the category prototype. In principle, numerous factors could increase stimulus uncertainty. One such factor is delay length. Work across a number of domains demonstrates that sensory representations become less precise, or more uncertain, over time (for review, see Magnusson and Greenlee 1999). Consistent with this, Huttenlocher, Hedges, and Duncan (1991) found in the spatial domain that memories of location showed more pronounced category bias after a long delay than a short one. Crawford, et al. (2000) showed that with estimates of line length, category bias increased when a delay was introduced, whereas bias due to perceptual factors (i.e., the Mueller-Llyer illusion) did not.

In a separate literature, research has examined the effect of cognitive load on decision-making. Cognitive load manipulations are secondary tasks a person engages in while simultaneously completing a task of interest. An extensive literature documents that cognitive resources are bounded and constrained, and that increasing cognitive load can compromise judgments (Cornelissen, Dewitte, and Warlop, 2011; Hinson, Jameson, & Whitney, 2003; Shiv & Fedorikhin, 1999; Swann, Hixon, Stein-Seroussi, & Gilbert, 1990; Van den Bos, Peters, Bobocel, and Ybema, 2006). Cognitive load increases anchoring effects (Bergman, Ellingsen, Johannesson, & Svensson, 2010; Oechssler, Roider, & Schmitz, 2009), limits the ability to process information (Gilbert, Pelham and Krull, 1988), decreases self-control (Mann and Ward, 2007), and decreases strategic behavior in game theory tasks such as the Prisoner's Dilemma (Duffy & Smith, 2014). However, to our knowledge, no study has employed a cognitive load task to study the central tendency bias in estimation.

If cognitive load increases uncertainty in memory, then category (prior) information would gain more influence, resulting in more bias in estimates. Although cognitive load has not been shown to affect basic perceptual processing, an analogous set of findings in the social cognition literature indicates that prior expectations influence judgments more when people are under cognitive constraints. Spontaneous trait inferences are more affected by stereotypes when people were required to retain an 8 digit number during the task (Wigboldus, Sherman, Franzese, & van Knippenberg, 2004). In addition, van Kippenberg, Dijksterhuis & Vermeulen (1999) showed that after reading about a crime, the availability of a negative stereotype affected punishment decisions, memory, and assessment of guilt when forced to read at a fast pace (high cognitive load), but not when reading at a comfortable pace.

We examine the effect of cognitive constraints on the degree to which category information influences stimulus estimates in two experiments. In the first, we manipulate the delay between the initial presentation of a stimulus and its estimation. This form of constraint is temporal: longer delays represent a greater constraint than shorter delays. Although this specific combination of task and constraint have not previously been examined, similar studies with in estimation with other tasks or stimulus domains lead to the strong prediction that increasing delay will increase the weight of category information. Second, we manipulate cognitive load by asking observers to remember a 2 digit (low load) or 6 digit (high load) number or letter string while they simultaneously estimate stimuli. If cognitive load functions like delay to increase the fine-grain information, then increasing cognitive load should also increase the effect of category information on stimulus estimates.

Experiment 1: Effect of delay

Methodology:

Participants: In this and the following study, undergraduates at Rutgers University (65 total, 40 females, 25 males) participated to fulfill a course requirement.

Design and Procedure: We employed a computer-administered serial reproduction task in which participants reproduced lines that varied in length. On each trial, a horizontal study line was presented for 1 second. After either a short (4 seconds) or long (8 seconds) delay period, a test line appeared, and participants were instructed to adjust the test line with a mouse until it matched the length of the study stimulus. Participants pressed enter to indicate satisfaction with their match, and the next trial began. Participants were debriefed at the end of the session. Study lines varied in 16-pixel increments from 80-368 pixels and were 5 pixels wide. Participants viewed 10 study lines at each of the 19 lengths. Study stimuli were presented in random order. The length of the test varied randomly. Delay was a between-participants variable, so each participants experienced either short or long delays.

Results

To analyze the data, we first calculated the estimation bias for each study stimulus by subtracting the actual length of the study line from the subject’s response. Positive bias thus means that participants remembered lines as being longer than they actually were; negative bias means that participants remembered lines as being shorter than they actually were. The bias data averaged across observers is shown in Figure 1. Consistent with previous results, participants overestimated the length of short lines, and underestimated the length of long lines.

To investigate the effect of delay on the central tendency bias, we performed a multiple regression analysis with dummy variables and compared the intercept and slopes of the two bias curves. We tested a two-level mixed effects model, with bias as the outcome variable. Fixed effects included actual length, a dummy variable for condition, the interaction between condition and actual length, the starting length of the response line, and the interaction between the starting length and condition. Participant intercepts and slopes were included as random effects. Table 1 provides a model comparison summary of the effects of sequentially adding fixed these effects to the model.

If participants adjusted estimates toward central values, the actual line length should negatively predict bias. Actual line length did significantly predicted bias (*b* = -0.291, *t*(12281) =

-14.666, $p = 0.0001$, 95% CI = [-0.330, -0.252]). Consistent with earlier findings from similar tasks, shorter lines were overestimated and longer lines underestimated.

As we predicted, there was a significant interaction between actual line length and condition ($b = -0.122$, $t(12281) = -3.82$, $p < 0.0001$, 95% CI = [-0.185, -0.059]), indicating that the slope of the bias curve was steeper in the long delay condition than in the short delay condition. Thus participants gave more weight to the category with longer delays.

In addition, we examined whether bias was affected by the starting value of the response line and if so, whether this effect also increased with delay. Starting line length also significantly predicted bias ($b = 0.136$, $t(12281) = 23.93$, $p < 0.0001$, 95% CI = [0.125, 0.147]). Participants' estimates were correlated with starting line length; that is, when the test line began longer, it also ended longer. This effect also interacted significantly with condition ($b = 0.020$, $t(12281) = 2.19$, $p = 0.03$, 95% CI = [-0.002, 0.038]), increasing slightly when the delay is longer.

Discussion

The main goal of Experiment 1 was to investigate the effect of delay on the strength of the central tendency bias. Increasing the delay increased the central tendency bias. This is consistent with a Bayesian framework in which stimulus estimates are produced by a combination of fine-grain information and category information. Increasing the delay increases the variability of the fine-grain representation, thus causing stimulus estimates to be more affected by the category (prior) information. Similar increases in bias with delay have also been reported for size (Ashourian and Lowenstein, 2011) and hue estimates (Olkkonen, McCarthy & Allred, in press).

Less predictably, the starting length of the reproduction line also influenced responses. This can be termed an anchoring effect. Such effects have not previously been examined in the context of the category adjustment model literature. Most prior studies used a fixed starting length that has a single value throughout the entire experiment. This anchoring effect was larger with longer delays. This may be due to the fact that the memory of the original stimulus degraded so much that the starting length of the reproduction line gets assimilated with the memory of the original target line. Alternatively, people may stop adjusting earlier under condition of greater delay.

Experiments 2: Cognitive Load Number and Letter Tasks

Methodology

Participants:

Thirty-five people (20 females, 15 males) participated in the number task, and thirty three people (22 females, 11 males) participated the letter task. We discarded participants who failed to complete the task (1 participants, letter task) or who achieved less than 50% correct in the high load condition (2 participants, letter task)

Design and Procedure:

The estimation task was very similar to Experiment 1, with the following minor adjustments. First, before the onset of the study line, participants viewed a 2-digit (low cognitive load) or 6-digit (high cognitive load) number or letter that they were instructed to remember. The study stimulus was presented for 1.5 seconds (instead of 1 second), and the delay between study and test was always 1.5 seconds (instead of 4 or 8 seconds). After participants indicated satisfaction with their match, they were prompted to type in the 2- or 6-digit number or letter.

To create number strings, we used integers. To create letter strings, we drew from the set BCFJKLPQSX. This letter choice prevented English-speakers from grouping letters into words. We used both tasks because numbers might be easier to “chunk” than letters.

To increase statistical power, cognitive load was a within-participants variable. In order to constrain the length of the experimental session to a reasonable time, we decreased the number of study lines tested from 19 to 9. Thus, study lines ranged from 96 to 352 pixels in 32 pixel increments. Participants saw each study line 10 times, 5 in the low-load condition, and 5 in the high-load condition.

Results:

Bias was calculated as in Experiment 1, and data averaged across observers are plotted for the number (Figure 2) and letter (Figure 3) tasks. Inspection of the data reveals a central tendency bias in all conditions, and that cognitive load had an effect similar to that of delay, with high load condition (solid lines) showing more bias (steeper slope) in both the number (Figure 2) and letter (Figure 3) tasks.

To statistically evaluate the pattern of results revealed by inspection of the data, we again tested a two-level mixed effects model, with cognitive load as condition instead of delay. Tables 2 (number task) and 3 (letter task) provide parallel model comparison summaries.

As in Experiment 1, we observed a central tendency bias. This central tendency bias was evidenced as the prediction of bias by actual line length (number task:, b = -0.052, t(2885) = -3.044, p = 0.0024, 95% CI= [-0.085, -0.018]; letter task, b = -0.044, t(2708) = -2.58, p = 0.0099 (95% CI: [-0.076, -0.012]). Also as in Experiment 1, shorter lines were overestimated and longer lines underestimated. However, the overall magnitude of the bias in Experiment 2 was less than in Experiment 1, likely because of the decreased delay.

In Figures 2 and 3, the high cognitive line (solid symbols and line) has a steeper slope than the low cognitive load line (open symbols, dashed line) indicating that cognitive load increased the central tendency bias. This observation was confirmed by interaction between actual line length and condition (number task: $b = -0.101$, $t(2885) = -7.79$, $p < 0.0001$, 95% CI = [-0.126, -0.077]; letter task: $b = -0.098$, $t(2708) = -7.321$, $p < 0.0001$, 95% CI = [-0.124, -0.073]). Thus it appears that participants give more weight to the category when under higher cognitive load.

As in Experiment 1, responses were anchored by starting length: starting line significantly predicted bias (number task: $b = 0.046$, $t(2885) = 5.32$, $p < 0.0001$, 95% CI = [.063, 0.029]; letter task: $b = 0.048$, $t(2708) = 5.497$, $p < 0.0001$, 95% CI = [0.0316, 0.0649]).. Thus, participants produced longer length estimates when the starting value was longer. Unlike in Experiment 1, however, we found no interaction between starting line length and load condition in either the number or load task (number task: $b = .012$, $t(2885) = 0.99$, $p = 0.324$, 95% CI = [-0.011, 0.035]; letter task: $b = 0.008$, $t(2708) = 0.6334$, $p = 0.526$, 95% CI = [-0.016, 0.032]). Thus there is no evidence that the anchoring and adjustment effect observed here increased when under cognitive load.

The pattern of results in the number and letter tasks identical, with the single exception that in the letter task there was a significant main effect of condition on length, indicating that observers overestimate more when under high cognitive load. This effect is small, however, and it affects only the intercept (and not the slope) of the bias line. It is also small compared to the other reported effects of central tendency bias and the effect of cognitive load on the size of the bias.

Discussion

In Experiment 2 we again replicated the central tendency bias. In addition, we found that high cognitive load, as operationalized by remembering 6 digit strings of numbers or letters, functions much like increasing delay: both increase the strength of the central tendency bias. Overall, we also observed the anchoring effect, although unlike the anchoring effect in Experiment 1, there was no interaction with load.

General Discussion

In two Experiments, we have demonstrated that both delay and cognitive load affect how people estimate stimuli. Increasing the delay and adding cognitive load increased the central tendency bias. Thus, category-level information influenced stimulus estimates more when memory or cognitive demands increased.

Although a number of studies have found that manipulating memory demands influences stimulus estimates (see Greenlee and Magnusson, 1999 for review), this study is to our knowledge the first to study this class of estimation biases under conditions of variable delay and cognitive load. The finding that category information affects estimates more under higher cognitive load suggests that, like increased delay, cognitive load interferes with the fine grain representation of the stimulus. In addition, this result suggests that activating and applying category information in the context of this task may be a relatively automatic process, as it does not appear to be compromised by the cognitive load manipulations used here. Because strong conclusions about automaticity cannot be made based only on these experiments, we suggest this as a topic for further research.

These findings are also the first to show that the starting length of the reproduction line influences estimates. Prior studies used a constant starting length of the reproduction line (Huttenlocher, et al. 2000, Crawford, Huttenlocher, & Engebretson, 2000) or randomized it without analyzing its effects (Duffy & Crawford, 2010). Here we find a significant anchoring effect in that estimates were biased toward the starting value of the response line, suggesting that people did not adjust it quite far enough. But unlike the central tendency bias, this effect did not increase with load.

Psychologists and economists are increasingly interested in how social conditions, such as poverty, put people under conditions of cognitive constraint that may affect decision making. Mani, Mullainathan, Shafir and Zhao (2014) compared poor and wealthy Americans on the tasks measuring fluid intelligence and cognitive control. They found that wealth did not affect performance on easy problems, but that poor Americans performed worse on hard problems. The effects of cognitive constraint are not only found between-observers: poor rural sugarcane farmers in India perform worse on similar cognitive tests before harvest (when they are worried about money) than they do after harvest (when they have just been paid). Biological markers were not indicative of physical stress; rather, poverty introduces high cognitive load. Thus, one direction for future research is to examine the effect of exogenous factors such as poverty or culture influence how people rely upon prior knowledge in estimation (Duffy & Kitayama, 2007).

The finding that participants use category information more under conditions of high cognitive load has implications for eyewitness testimony.. Witnesses to a crime are likely under cognitive load due during interrogation due to the cognitive and emotional stress they endure (Christiansen, 1992); category (or prior) information may thus have a greater effect on their memories. Accurate eyewitness testimony is critical for correctly identifying perpetrators. However, if witnesses rely more on categories under these conditions of cognitive constraint, they may be more likely to report seeing a category prototype (e.g. this is what typical perpetrators of crimes look like) rather than the specific instance (e.g. this is the perpetrator I saw). Thus, high cognitive load may exacerbate negative stereotyping in eyewitness testimony.

Works Cited

Akaike, H. (1974). A new look at the statistical model identification, IEEE Trans. *Automatic Control 19*, 716–723. DOI: 10.1109/TAC.1974.1100705

Allred, S., Duffy, S., & Smith, J. (under revision) Cognitive load and strategic sophistication.

Ashourian, P., & Loewenstein, Y. (2011). Bayesian inference underlies the contraction bias in delayed comparison tasks. *PloS One*, *6*(5), e19551. doi:10.1371/journal.pone.0019551

Bergman, O., Ellingsen, T., Johannesson, M., & Svensson, C. (2010). Anchoring and cognitive ability. *Economics Letters, 107,* 66–68. DOI: 10.1016/j.econlet.2009.12.028

Christianson, S. Å. (1992). Emotional stress and eyewitness memory: a critical review. *Psychological bulletin*, *112*, 284-309.

Cornelissen, G., Dewitte, S., and Warlop, L. (2011). Are social value orientations expressed automatically? Decision making in the dictator game, *Personality and Social Psychology Bulletin, 37,* 1080--1090.

Crawford, L.E., & Duffy, S. (2010). Sequence effects in estimating spatial location. *Psychonomic Bulletin and Review, 15,* 576-588. DOI:10.3758/PBR.17.2.224

Crawford, L.E., Duffy, S., & Falcone, D. (in preparation). Effect of estimating stimuli on inductive category formation.

Crawford, L. E., Huttenlocher, J., & Engebretson, P. H. (2000). Category effects on estimates of stimuli: Perception or reconstruction. *Psychological Science, 11*(4), 280-284. doi: 10.1111/1467-9280.00256

Crawford, L. E., Huttenlocher, J., & Hedges, L. V. (2006). Within-category feature correlations and Bayesian adjustment strategies. *Psychonomic Bulletin & Review, 13*(2), 245-250. DOI: 10.3758/BF03193838

Duffy, S., & Crawford, L.E. (2008). Primacy or recency effects in the formation of inductive categories. *Memory and Cognition, 36,* 567-577. DOI:10.3758/MC.36.3.567

Duffy, S., & Kitayama, S. (2007). Mnemonic context effect in two cultures: An examination of culturally contingent attention strategies. *Cognitive Science, 31,* 1009-1020. DOI: 10.1080/03640210701703808

Duffy, S. & Smith, J. (2014). Are there brains in games? Cognitive load in the multiple player prisoner's dilemma game. *Journal of Behavioral and Experimental Economics, 47-56.* DOI: 10.1016/j.socec.2014.01.006

Duffy, S., Huttenlocher, J., & Crawford, L. E. (2006). Children use categories to maximize accuracy in estimation. *Developmental Science, 9*(6), 597-603. DOI: 10.1111/j.1467-7687.2006.00538.x

Duffy, S., Huttenlocher, J., Hedges, L. V., & Crawford, L. E. (2010). Category effects on stimulus estimation: Shifting and skewed frequency distributions. *Psychonomic Bulletin & Review, 17,* 224-230. DOI:10.3758/PBR.17.2.224

Gilbert, D. T., Pelham, B. W., & Krull, D. S. (1988). On cognitive busyness: When person perceivers meet persons perceived. *Journal of personality and social psychology, 54*, 733.

Hinson, J. M., Jameson, T. L., and Whitney, P. (2003). Impulsive decision making and working memory, *Journal of Experimental Psychology: Learning, Memory, and Cognition, 29,* 298--306.

Hollingworth, H. L. (1910). The central tendency of judgment. *Journal of Philosophy, Psychology and Scientific Methods, 7,* 461-468. DOI:10.2307/2012819

Huttenlocher, J., Hedges, L. V., & Duncan, S. (1991). Categories and particulars: prototype effects in estimating spatial location. *Psychological Review*, *98*(3), 352.

Huttenlocher, J., Hedges, L. V., & Vevea, J. L. (2000). Why do categories affect stimulus judgment? *Journal of Experimental Psychology: General*, *129*, 220-241.

Magnussen, S., & Greenlee, M. W. (1999). The psychophysics of perceptual memory. *Psychological Research*, *62*, 81–92. DOI:10.1007/s004260050043

Jazayeri, M., & Shadlen, M. N. (2010). Temporal context calibrates interval timing. *Nature Neuroscience*, *13*(8), 1020–6. DOI:10.1038/nn.2590

Mani, A., Mullainathan, S., Shafir, E., & Zhao, J. (2013). Poverty impedes cognitive function. *Science, 341*, 976-980. DOI:10.1126/science.1238041

Mann, T., & Ward, A. (2007). Attention, self-control, and health behaviors. *Current Directions in Psychological Science*, *16*, 280-283. Downloaded from http://www.jstor.org.proxy.libraries.rutgers.edu/stable/20183216

Oechssler, J., Roider, A. and Schmitz, P. W. (2009) Cognitive abilities and behavioral biases. *Journal of Economic Behavior and Organization, 72,* 147–152. DOI: 10.1016/j.jebo.2009.04.018

Olkkonen, M., & Allred, S. R. (2014). Short-Term Memory Affects Color Perception in Context. *PLoS ONE*, *9*(1), e86488. doi:10.1371/journal.pone.0086488

Olkkonen, M. McCarthy, P. F, & Allred, S.R (*in press*). The central tendency bias in color perception: effects of internal and external noise. *Journal of Vision*.

Shiv, B. and Fedorikhin, A. (1999). Heart and mind in conflict: The interplay of affect and cognition in consumer decision making, *Journal of Consumer Research*, *26,* 278-292.

Swann, W. B., Hixon, G., Stein-Seroussi, A., and Gilbert, D. T. (1990). The fleeting gleam of praise: Cognitive processes underlying behavioral reactions to self-relevant feedback," *Journal of Personality and Social Psychology, 59,* 17-26.

Van den Bos, K., Peters, S. L., Bobocel, D. R., and Ybema, J. F. (2006) On preferences and doing the right thing: Satisfaction with advantageous inequity when cognitive processing is limited. *Journal of Experimental Social Psychology, 42,* 273--289.

Van Knippenberg, A. D., Dijksterhuis, A. P., & Vermeulen, D. (1999). Judgement and memory of a criminal act: The effects of stereotypes and cognitive load. *European Journal of Social Psychology*, *29*, 191-201. DOI:10.1002/(SICI)1099-0992(199903/05)29:2/3<191

Wigboldus, D. H., Sherman, J. W., Franzese, H. L., & Knippenberg, A. V. (2004). Capacity and comprehension: Spontaneous stereotyping under cognitive load. *Social Cognition*, *22*(3), 292-309. DOI:10.1177/0272989X09341751

Table 1: For Experiment 1, Model comparison for linear mixed effects models of bias. Each row represents a different linear model. Each successive model adds one more parameter (indicated in column 1); the total number of parameters is reflected in the second column (df). Parameters were either fixed (F) or random (R). Column 4 shows the ratio of the log-likelihoods of the fit provided by the two models listed in the fourth column. P represents the significance of the model calculated using AIC (Akaike, 1974). Briefly, it indicates whether the improvement of the model fit justifies the inclusion of the extra parameter.

Model	df	Log ratio	Model Comparison	*P*
Bias				
1. Intercept Only	2			
2. Participant (R)	3	279.50	1 vs 2	<0.0001
3. Actual length (slope) (F)	4	4088.03	2 vs 3	<0.0001
4. Participant Slope (R)	6	606.88	3 vs 4	<0.0001
5. Condition (F)	7	0.295	4 vs 5	0.59
6. Condition × Actual length (F)	8	13.31	5 vs 6	<0.0001
7. Starting size (F)	9	996.79	6 vs. 7	<0.0001
8. Staring Size × Condition (F)	10	4.80	7 vs. 8	<0.05

Table 2. Model comparison for linear mixed effects models of bias.

Model	df	Log ratio	Model Comparison	*P*
Bias				
1. Intercept Only	2			
2. Participant (R)	3	251.08	1 vs 2	<0.0001
3. Actual length (slope) (F)	4	214.45	2 vs 3	<0.0001
4. Participant Slope (R)	6	96.15	3 vs 4	<0.0001
5. Condition (F)	7	0.05	4 vs 5	0.83
6. Condition × Actual length (F)	8	60.01	5 vs 6	<0.0001
7. Starting size (F)	9	73.59	6 vs. 7	<0.0001
8. Staring Size × Condition (F)	10	0.98	7 vs. 8	0.32

Table 3. *Model comparison for linear mixed effects models of bias.*

Model	df	Log ratio	Model Comparison	*p*
Bias				
1. Intercept Only	2			
2. Participant (R)	3	187.98	1 vs 2	<0.0001
3. Actual length (slope) (F)	4	165.34	2 vs 3	<0.0001
4. Participant Slope (R)	6	80.23	3 vs 4	<0.0001
5. Condition (F)	7	3.91	4 vs 5	<0.05
6. Condition × Actual length (F)	8	52.95	5 vs 6	<0.0001
7. Starting size (F)	9	68.71	6 vs. 7	<0.0001
8. Staring Size × Condition (F)	10	0.40	7 vs. 8	0.53

Figure 1: Delay affects the magnitude of the central tendency bias. Bias (actual line length subtracted from estimated line length) is plotted as a function of stimulus size for short delay (open symbols) and long delay (solid symbols) conditions. Data points are averages across all trials for all observers. Solid (long delay) and dashed (low-delay) lines are best fit through the data. Solid horizontal line represents zero bias, or veridical memory.

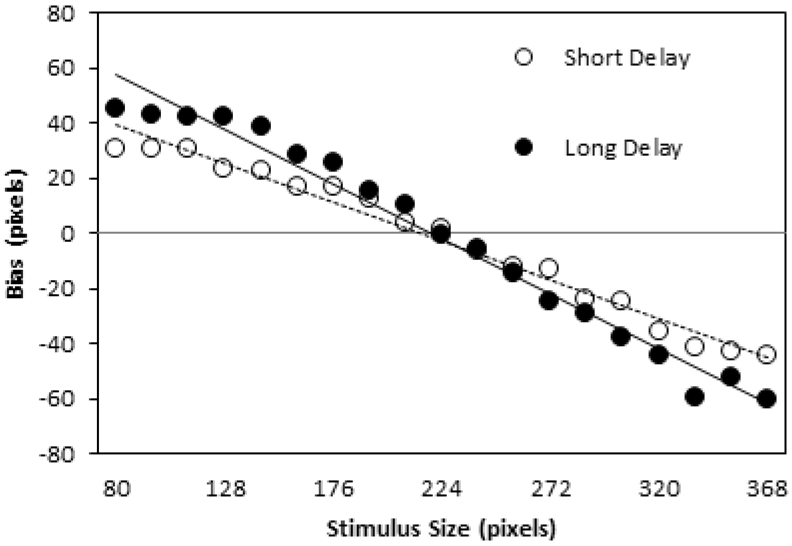

Figure 2: Cognitive load affects the magnitude of the central tendency bias in the number task. Bias (actual line length subtracted from estimated line length) is plotted as a function of stimulus size for low load (open symbols) and high load (solid symbols) conditions. Data points are averages across all trials for all observers. Solid (long delay) and dashed (low-delay) lines are best fit through the data. Solid horizontal line represents zero bias, or veridical memory.

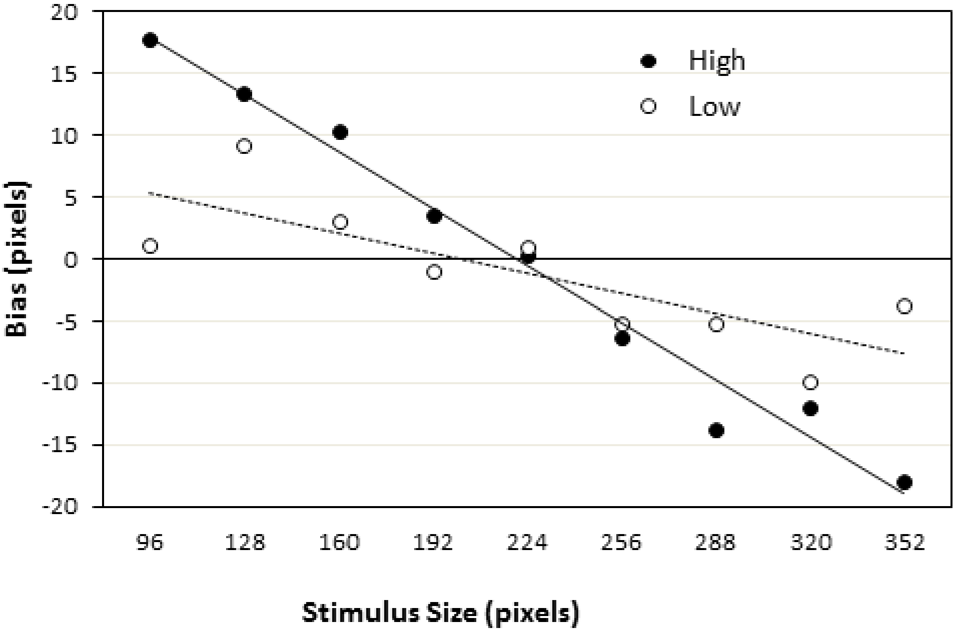

Figure 3: Cognitive load affects the magnitude of the central tendency bias in the letter task. Bias (actual line length subtracted from estimated line length) is plotted as a function of stimulus size for low load (open symbols) and high load (solid symbols) conditions. Data points are averages across all trials for all observers. Solid (long delay) and dashed (low-delay) lines are best fit through the data. Solid horizontal line represents zero bias, or veridical memory.