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The interaction of map resolution and spatial abilities on map learning

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Abstract

This study investigated how the addition of enhanced perceptual detail in a navigation interface interacts with learner characteristics and ultimately impacts learning; specifically memory for a route on a map. Previous research has shown both facilitative and prohibitive effect of adding perceptual detail to user interfaces. However, it is not clear how adding this kind of resolution might also interact with learner abilities. This study evaluated how well routes were remembered from maps that were either enhanced with actual satellite photography or presented in more traditional (low resolution) form by learners who differed in spatial ability. Results indicated that learners recalled a mapped route significantly better in the low perceptual detail condition than in the high detail condition and spatial visualization ability significantly predicted success on these tasks whereas mental rotation ability did not. Thus, it appears that the addition of perceptual detail not only affects learning, but also interacts with learner ability.

Keywords: Map learning; Perceptual detail; Spatial abilities

1. Introduction

Recent advances in technology have enabled designers to place increasing amounts of detail on informational and navigational displays without the worry of storage or cost. As a result, designers are often faced with the task of determining how much perceptual information is appropriate and necessary for the completion of various tasks. While the mantra 'more is better' is often the norm with the evolution of technology and devices, the question remains as to how this potential increase in resolution might impact understanding of the material to be learned. Additionally, will such increases also interact with individual user characteristics and further complicate the effectiveness of such interfaces?

1.1. How much is too much?

It has been suggested that external displays should closely resemble the actual phenomenon they are meant to represent as they would then more accurately match the original, internal perceptions of the learner (Roscoe, 1968; Tversky et al., 2002). The closer the match between external and internal, the better performance should be. Adding enhanced perceptual detail has been shown to facilitate the formation of conceptual understanding (Goldstone and Barsalou, 1998) and also the recognition of similarities between different visual scenes (Marzolf and DeLoache, 1994). In terms of map usage, it has also been suggested that the more closely a map represents the real world, the better users should be able to use them (Downs, 1981; Guelke, 1979). Indeed, enhancing the number or type of features on a map has been shown to increase recall of map facts (Peterson et al., 1991; Schwartz and Kulhavy, 1981).

However, it has also been demonstrated that the presence of more perceptual detail can lead to worse learning. For example, perceptually rich displays caused learners to become fixated on the perceptual surface features, rather than the deeper relationships between items (Goldstone and Sakamoto, 2003; Sloutsky et al., 2005; Zacks et al., 1998). Recent work has also shown that the nature and amount of map features, specifically

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whether they are verbal or non-verbal, do interact and influence subsequent performance (Brunyé et al., 2007). For example, the addition of relevant graphical information an informal street map increased the amount of time needed to reach a destination (Kovach et al., 1988). Similarly, the addition of simple features such as color or icon type does not appear to positively impact learning from maps (Griffin and Robinson, 2005; Kulhavy et al., 1993).

For this reason, it has been suggested that displays should not contain this kind of additional, non-optimal resolution for the simple reason that not all data might be informative or necessary to accomplish a given task (Mayer, 1989; Mayer et al., 2001; Tufte, 2001; Tullis, 1983). Similarly, such additional material might in fact make it more difficult to identify more pertinent information in the display, especially for those individuals that are lower in relevant cognitive abilities (Sanchez and Wiley, 2006). It is possible that the amount of perceptual detail presented in a display might interact with the characteristics of the individual who is asked to interact with such interfaces, which could be especially problematic for low-ability individuals. For example, in a primarily spatial task such as learning a travel route, it is possible that adding non-optimal (but not irrelevant in the traditional sense) perceptual detail can be considered akin to increasing the amount of information the learner would have to encode or manipulate in their representation (as these details are likely 'tied' to the conceptual units they are attached to). In such situations, how well a person can process such information (e.g., spatial abilities (SA)) should predict their success at dealing with the task, and low-ability learners might be at a distinct disadvantage (Kovach et al., 1988; Kulhavy and Stock, 1996; Lobben, 2004; Sholl and Egeth, 1982; Uttal, 2000).

1.2. Spatial abilities

While recent research has moved towards finer discriminations in multiple specific kinds of spatial abilities (Hegarty and Waller, 2006; Kozhevnikov and Hegarty, 2001; Zacks et al., 2002), spatial abilities can be grossly segmented into two sub-types of ability: those that tap mental rotation (MR) and those that tap the ability to spatially visualize (SV) and re-conceptualize an existing spatial representation (Carroll, 1993; Cooper, 1975; Cooper and Shepard, 1973; Mumaw et al., 1984; Pellegrino and Hunt, 1991). Although generally recognized as separate abilities by many (Miyake et al., 2001), these two sub-types of spatial ability are usually highly correlated and difficult to differentiate (Carroll, 1993; Just and Carpenter, 1985; Stumpf and Eliot, 1995).

SA have been shown to predict performance on a variety of higher level tasks that require visuospatial information processing, such as mechanistic reasoning tasks (Hegarty and Sims, 1994; Hegarty and Steinhoff, 1997), and also general reasoning/problem-solving tasks (for a review, see Hegarty and Waller, 2006). Spatial abilities have also been connected to first-person navigation in virtual mazes (Moffat et al., 1998) and have been speculated to underlie sex differences in route learning (Galea and Kimura, 1993). However, it is of interest to determine whether these abilities can also predict task performance where the only difference is the perceptual context and not the visuospatial demand. In other words, can perceptual detail be considered a relevant characteristic when evaluating the overall demands of the task, and is it possible for SA to reliably predict how well participants can deal with the level of detail (when processing considerations are simple and constant)?

This study investigates the advantages and disadvantages of providing increased pictorial detail in a map display where participants were asked to remember a marked route. On one hand, providing additional perceptual detail may make the display easier to encode due to redundant coding and increased opportunity to make connections between features (Craik and Tulving, 1975; Goldstone and Barsalou, 1998; Lovelace et al., 1999). However, it is more likely that additional perceptual detail may increase the overall amount of information to be manipulated, which could negatively impact performance for low-ability individuals who might have difficulty processing this additional information (Pellegrino and Hunt, 1991).

2. Methods

2.1. Participants

Forty ($N = 40$) students at a public southwestern US university participated for course credit. All participants were familiar with how to use maps as acknowledged by verbal report prior to the session.

2.2. Design

This experiment was conducted within groups utilizing a Latin-square design. Based on counterbalancing condition, half of the participants viewed a highly detailed map and then a low detailed map and the remaining half of the participants viewed a low detailed map followed by a highly detailed map.

2.3. Materials

2.3.1. Maps

Participants viewed a MS Power Point presentation, which contained two neighborhood maps. One of these maps was enhanced with perceptual detail (i.e., satellite imagery) and the other was presented in normal (low) detail with gray blocks with no additional features representing city blocks, based on counterbalancing condition. Satellite imagery used in the high perceptual condition was taken from an urban setting (e.g., Chicago, IL) in order to insure uniform block size and density of housing, buildings, etc. The perceptual detail of these maps was counterbalanced by condition and both maps comprised 32 square blocks. On both maps, streets were labeled alphabetically in one direction (e.g., A, B, C) and numerically in the other (12th, 13th, 14th), in ascending order. This labeling was intentional, in order to make it easier for participants to represent or recall the otherwise unfamiliar neighborhood, and further ensure that any differences were due to the manipulation and not unfamiliarity with the task setting. In addition, to ensure that the labels were legible and not lost in the background, labels were outlined in red. Routes were marked on these maps with a transparent green line (60%), analogous to most popular mapping programs. Each route contained seven left turns and seven right turns generated by the experimenters, and routes were of approximately equal length (22 blocks vs. 23 blocks). Example maps with routes are presented in Fig. 1.

2.3.2. *SA measures*

Participants also completed Set 1 of both paper folding (PF) and cube comparisons (CC) tasks (tests VZ-2 and S-2 in the French Reference Kit; French et al., 1963). The paper folding task is considered a measure of spatial visualization, whereas the cube comparisons task is considered a measure of mental rotation ability. Both tasks have been shown to be highly correlated and are considered prototypical measures of spatial ability and have been used extensively as such (Kane et al., 2004). Within this sample, these tasks were also significantly correlated at $r(40) = .42$, $p < .05$, which is consistent with prior research (Kane et al., 2004).

2.4. *Procedure*

Participants were instructed that they had been elected to supervise a local neighborhood parade. Maps of the neighborhood and the suggested parade route were provided to them by the city, however due to their lateness of arrival, participants would only have a few minutes to study both the maps and route. Participants first studied map 1 of the neighborhood that was either highly detailed or low detailed (varied by counterbalancing condition), which contained no route information. Participants were instructed to memorize all the street names of the neighborhood, as they would have to label a map for their volunteers. This initial map was only available for 1 min.

Participants were then asked to recall the street names on an unlabeled version of the same map they had just viewed.

Participants were then shown the same map as before, except a route was now superimposed on the map, and marked with a transparent green line. Start and end points were indicated on the map by a green dot (start) and a red dot (end). Participants viewed this route map for 2 min. After viewing the route map, participants were then given a printout of the same map, with both streets and start/end points indicated (but no route), and asked to redraw the route. Participants were given 1 min. to reproduce the route.

Participants then completed the PF and CC tasks.

Participants then repeated the above procedure with map 2, which contained the opposite amount of details

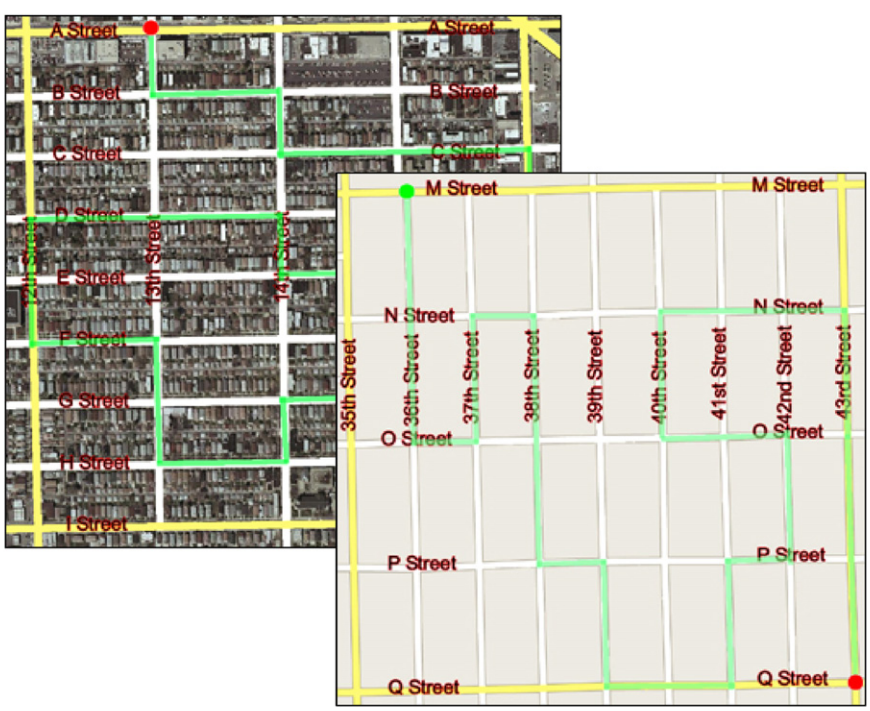

Fig. 1. Sample low- and high-resolution maps.

from map 1 (e.g., instead of high detail, low detail), based on counterbalancing condition. After completion of this second map condition, participants were debriefed and dismissed. The entire experiment took no longer than 30 min.

3. Results

In order to examine the impact of perceptual detail, all results were evaluated using a repeated measures ANOVA comparing the high detail to low detail condition. Counterbalancing condition was also included in the analyses as a between-subjects variable. This resulted in a mixed design, with perceptual detail being compared within groups and counterbalancing condition compared across groups.

Counterbalancing condition produced no significant main effects or interactions ($p > .05$) for all subsequent analyses. For this reason, only the main effects of perceptual detail are reported here.

3.1. Neighborhood street recall

All participants successfully recalled *all* street names for both maps viewed. Again, this ensures that any subsequent effects are due to the experimental manipulation, rather than a lack of basic familiarity with the neighborhood where the route was situated.

3.2. Graphical route reproduction

Accuracy of route reproduction was evaluated by how many correct turns were included in the re-drawing of the route by each participant. A correct turn was considered any turn that was consistent in absolute direction (both in direction of travel before and after turn) AND intersection with the original route. Thus, it was possible for a participant to go off the original route through an incorrect turn(s), but then make a correct turn to and 'get back on track' with the original route later in the sequence.

The number of total overall turns (correct plus incorrect) contained in both the low ($M = 12.38$, $SD = 2.48$) and high perceptual detail ($M = 12.03$, $SD = 3.12$) map reproductions was identical, $F(1, 38) < 1$ (Fig. 2). This finding is important as it suggests that any subsequent findings are not due to one condition merely having more opportunity to include correct or incorrect turns.

Descriptive statistics for the number of correct turns are available in Table 1. In terms of the number of correct turns included in the graphical reproduction, results indicated that there was a significant main effect of detailed resolution on performance ($F(1, 38) = 5.41$, $MSe = 11.64$, $p < .05$, $\eta^2 = .13$, see Fig. 2). Participants recalled significantly more correct turns within the route when the route was viewed with low detail versus when the route included the high-resolution satellite imagery. This suggests that including the extra detail (as in the high-resolution map) negatively impacted how well participants could recall correct turns within the desired route. Further, as the overall number of turns was equal between conditions, this also suggests that participants were more likely to make incorrect turns in the high-resolution condition.

Taken together, these results suggest that when participants memorize route information from low detail maps, even though they produce routes of equal length, participants are more likely to produce correct turns (and also fewer incorrect turns) when the route is learned from a low-resolution map. This suggests that the inclusion of high detail imagery does not positively affect map learning.

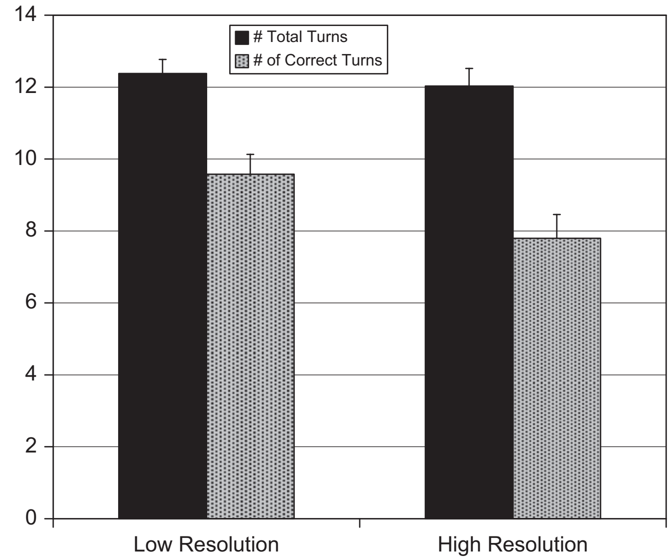

Fig. 2. Number of total and correct turns by map resolution condition (error bars represent standard errors of the means).

Table 1
Descriptive statistics for learning measures and spatial ability measures.

	$M(SD)$	Range	Skew ($SE = .37$))	Kurtosis ($SE = .73$)
Low correct turns	9.58(3.49)	3–14	−.15	−1.34
High correct turns	7.80(4.18)	2–14	.42	−1.26
PF	5.65(1.66)	3–9	.06	−.63
CC	11.25(3.51)	3–17	−.22	−.54

Table 2
Correlations between spatial ability measures and map learning measures.

	Low correct turns	Low total turns	High correct turns	High total turns
PF	.29	.26	.45*	.19
CC	.12	.03	.25	.08

* $p < .05$.

3.3. Spatial abilities and route reproduction

Descriptive statistics for these SA measures are available in Table 1. Correlations between PF, CC and route recall are available in Table 2. The PF task was significantly correlated with the number of correct turns ($r(40) = .45$, $p < .05$) produced for the high perceptual detail map, and was marginally correlated with the number of correct turns ($r(40) = .29$, $p = .07$) in the low-resolution condition. PF was not correlated with the overall number of turns in either resolution condition.

Conversely, the CC task was not significantly correlated with either the number of correct or incorrect turns in either resolution condition ($p > .05$), nor was it correlated with the number of overall turns in either condition.

In order to evaluate how these abilities predict performance in these two map resolution conditions, separate linear regression analyses for correct turns in both high- and low-resolution conditions were conducted. Both spatial visualization ability and mental rotation ability were entered simultaneously in the regression model to evaluate the amount of unique predictive variance for each of these measures of map memory.

In the low-resolution condition, neither PF nor CC significantly predicted the number of correct turns ($R^2 = .04$, F (2, 37) = 1.73, $p > .05$). Thus, spatial abilities overall do not appear to be significantly related to map memory in low perceptual resolution conditions. In the high-resolution condition, spatial abilities did predict the number of correct turns ($R^2 = .16$, F (2, 37) = 4.81, $p < .01$). However, only PF was significantly related to the number of correct turns ($\beta = .42$, $p < .01$). CC did not significantly predict the number of correct turns ($\beta = .08$, $p > .05$) in the high-resolution condition. These results indicate that spatial abilities (specifically spatial visualization ability) are only relevant in situations where there is high perceptual load or detail, and that spatial abilities overall are not predictive of map memory in low perceptual resolution conditions.

A final related question is whether the impact of map resolution affects high and low spatial visualizers equally. This raw relationship between resolution and spatial visualization is presented in Fig. 3 where regression lines for the PF task are presented for the number of correct turns in both low- and high-resolution conditions. As is visible in Fig. 3, the increase of resolution specifically impacted the performance of individuals who are low in spatial visualization ability, but does not appear to impact high performing individuals. To further solidify this point, participants were divided into either low ($n = 17$) or high ($n = 23$) spatial visualization ability groups based on a median split of performance on the PF task. Results indicated that high spatial individuals produced an equal number of correct turns in the low ($M = 10.57$, $SD = 3.41$) and high ($M = 9.26$, $SD = 4.29$; $t(22) = 1.27$, $p > .05$) resolution conditions. However, low spatial individuals produced significantly few turns in the high-resolution condition ($M = 5.82$, $SD = 3.17$) than in the low-resolution condition ($M = 8.24$, $SD = 3.23$; $t(16) = 2.09$, $p < .05$). Therefore, it appears that additional resolution was especially taxing for low spatial visualization ability individuals.

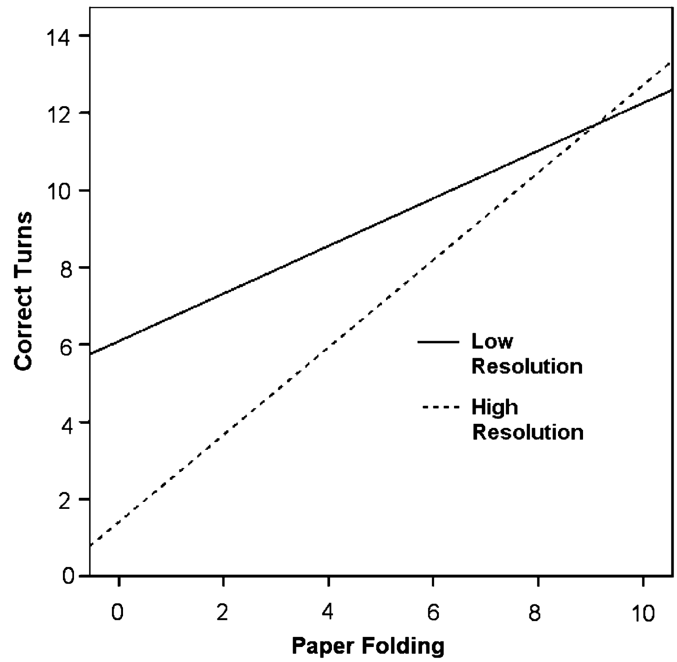

Fig. 3. Regression lines for spatial visualization ability on number of correct turns by map resolution condition.

4. Discussion

The results of this experiment suggest that including extra detail in navigational displays can negatively impact remembering a route presented on a map. When asked to graphically reproduce the route, participants included more correct turns in their responses when the route was learned from a map that was low in perceptual detail, rather than with high detail. Thus, it appears that map learning is significantly better when the route is presented in a low-resolution display. This suggests that while it is possible to add such information with little to no trouble technically speaking, there is a distinct cost of these additions in terms of performance.

This finding is consistent with other research which has found that more generalized (and thus less detailed) displays produce better recall of map information (Brunye et al., 2007). While other studies have found that adding additional featural information does positively impact remembering, this effect is usually attributable to the idea that these features activate relevant prior knowledge that can then be used to enhance encoding or recall (Guelke, 1979; Kulhavy and Stock, 1996). In the current study, as participants did not have any opportunity to activate specific prior knowledge (i.e., given the lack of defining features in the urban satellite imagery), it is not surprising that this featural information did not produce a subsequent learning benefit. It is possible that in this case, these features were instead reduced to non-informative decoration, which has been shown not to facilitate map learning (Griffin and Robinson, 2005; Kulhavy et al., 1993), and also produces additional demands for low-ability learners (Sanchez and Wiley, 2006).

Further, it also appears that the success of remembering a route in high-resolution displays is directly related to spatial visualization ability and *not* mental rotation. This finding suggests that not only is performance related to perceptual resolution, but is also contingent on the individual characteristics of the user. It appears that the perceptual load in the high-resolution condition was especially demanding for low visualization ability individuals. Given that the task requires participants to not only encode the spatial information of the map itself, but also remember the route within the map (which could be seen to require one to visualize turns, etc.), this high correlation of spatial visualization ability with map learning performance is not totally unexpected. The fact that mental rotation was not predictive of map learning in either condition is also not totally unexpected, as this map learning task does not require participants to mentally rotate either their perspective or any material on the map itself. However it is possible that, were this task to be modified to require mental rotation, one would then expect a correlation of this measure with performance (Darken and Cevik, 1999; Sholl and Egeth, 1982).

Overall, these data represent a first step in investigating the issues of data density (specifically in maps) and the interaction of this data density with learner characteristics. This work bears implications for the design of realistic displays and other interfaces that are used to portray actual phenomenon. Again, while it is possible to 'saturate' the display with rich sources of information that are now becoming readily available, this work cautions against such manipulations, at least for displays that could be used by low spatial ability individuals. At the very least, a careful consideration of the individual characteristics of the learner should be conducted prior to their inclusion.

Future research might focus on additional terrains that are less grid-orientated and vary in their detail as it is of interest to determine at what point such perceptual features cease to fade into the background and instead become more diagnostic. By design, the maps used in this experiment were all of urban landscapes with little variation; however, it would be interesting to see whether the inclusion of features that are not so uniform would actually reverse this effect. For example, such features might provide an additional means of orientating oneself within the map, thus providing a salient cue to activate prior knowledge (Verdi and Kulhavy, 2002) which would subsequently increase performance. Also, it seems worthwhile to continue to explore the interaction of map learning with other relevant cognitive abilities, such as controlled attention (e.g., WMC) or prior knowledge. Additionally, rather than just examining overall learning, it would also be worthwhile to explore the possibility of how individual differences influence the rate or speed of map learning.

References

Brunyé, T.T., Taylor, H.A., Worbys, M., 2007. Levels of details in descriptions and depictions of geographic space. Spatial Cognition and Computation 7 (3), 227–266.

Carroll, J.B., 1993. Human Cognitive Abilities: A Survey of Factor Analytic Studies. Cambridge University Press, Cambridge, England.

Cooper, L.A., 1975. Mental transformations of random two-dimensional shapes. Cognitive Psychology 7, 20–43.

Cooper, L.A., Shepard, R.N., 1973. Chronometric studies of the rotation of mental images. In: Chase, W.G. (Ed.), Visual Information Processing. Academic Press, New York.

Craik, F.I.M., Tulving, E., 1975. Depth of processing and the retention of words in episodic memory. Journal of Experimental Psychology: General 104, 268–294.

Darken, R.P., Cevik, H., 1999. Map usage in virtual environments: orientation issues. Proceedings of IEEE Virtual Reality 1999, 133–140.

Downs, R.M., 1981. Maps and metaphors. The Professional Geographer 33 (3), 287–293.

French, J.W., Ekstrom, R.B., Price, L.A., 1963. Kit of Reference Tests for Cognitive Factors. Educational Testing Service, Princeton, NJ.

Galea, L.A.M., Kimura, D., 1993. Sex differences in route-learning. Personality and Individual Differences 14 (1), 53–65.

Goldstone, R.L., Barsalou, L.W., 1998. Reuniting perception and conception. Cognition 65 (2-3), 231–262.

Goldstone, R.L., Sakamoto, Y., 2003. The transfer of abstract principles governing complex adaptive systems. Cognitive Psychology 46, 414–466.

Griffin, M.M., Robinson, D.H., 2005. Does spatial or visual information in maps facilitate text recall? Reconsidering the conjoint retention hypothesis. Educational Technology, Research & Development 53 (1), 23–36.

Guelke, L., 1979. Perception, meaning and cartographic design. Cartographica: The International Journal for Geographic Information and Geovisualization 16 (1), 61–69.

Hegarty, M., Sims, V.K., 1994. Individual differences in mental animation during mechanical reasoning. Memory & Cognition 22 (4), 411–430.

Hegarty, M., Steinhoff, K., 1997. Individual differences in use of diagrams as memory in mechanical reasoning. Learning and Individual Differences 9 (1), 19–44.

Hegarty, M., Waller, D., 2006. Individual differences in spatial abilities. In: Shah, P., Miyake, A. (Eds.), Handbook of Visuospatial Thinking. Cambridge University Press, Cambridge.

Just, M.A., Carpenter, P.A., 1985. Cognitive coordinate systems: accounts of mental rotation and individual differences in spatial ability. Psychological Review 92, 137–172.

Kane, M.J., Hambrick, D.Z., Tuholski, S.W., Wilhelm, O., Payne, T.W., Engle, R.W., 2004. The generality of working memory capacity: a latent-variable approach to verbal and visuospatial memory span and reasoning. Journal of Experimental Psychology: General 133 (2), 189–217.

Kovach, R.C., Surrette, M.A., Aamodt, M.G., 1988. Following informal street maps: affects of map design. Environment and Behavior 20 (6), 683–699.

Kozhevnikov, M., Hegarty, M., 2001. A dissociation between object-manipulation and perspective-taking spatial abilities. Memory & Cognition 29, 745–756.

Kulhavy, R.W., Stock, W.A., 1996. How cognitive maps are remembered. Annals of the Association of American Geographers 86 (1), 123–145.

Kulhavy, R.W., Stock, W.A., Werner-Bellman, L., Klein, J.D., 1993. Properties of maps that improve recall of associated text. Cartography and Geographic Information Science 20 (3), 151–156.

Lobben, A.K., 2004. Tasks, strategies, and cognitive processes associated with navigational map reading: a review perspective. The Professional Geographer 56 (2), 270–281.

Lovelace, K.L., Hegarty, M., Montello, D.R., 1999. Elements of good route directions in familiar and unfamiliar environments. In: Freksa, C., Mark, D.M. (Eds.), Spatial Information Theory: Cognitive and Computational Foundations of Geographic Information Science. (Lecture Notes in Computer Science 1661). Springer, Berlin.

Marzolf, D.P., DeLoache, J.S., 1994. Transfer in young children's understanding of spatial representations. Child Development 65 (1), 1–15.

Mayer, R.E., 1989. Systematic thinking fostered by illustrations in scientific text. Journal of Educational Psychology 81 (2), 240–246.

Mayer, R.E., Heiser, J., Lonn, S., 2001. Cognitive constraints on multimedia learning: when presenting more material results in less understanding. Journal of Educational Psychology 93 (1), 187–198.

Miyake, A., Friedman, N.P., Rettinger, D.A., Shah, P., Hegarty, M., 2001. How are visuospatial working memory, executive functioning, and spatial abilities related? A latent-variable analysis. Journal of Experimental Psychology: General 130 (4), 621–640.

Moffat, S.D., Hampson, E., Hatzipantelis, M., 1998. Navigation in a "virtual" maze: sex differences and correlation with psychometric measures of spatial ability in humans. Evolution and Human Behavior 19, 73–87.

Mumaw, R.J., Pellegrino, J.W., Kail, R.V., Carter, P., 1984. Different slopes for different folks: process analysis of spatial aptitude. Memory and Cognition 12 (5), 515–521.

Pellegrino, J.W., Hunt, E.B., 1991. Cognitive models for understanding and assessing spatial abilities. In: Rowe, H.A.H. (Ed.), Intelligence: Reconceptualization and Measurement. Lawrence Erlbaum Associates, Mahwah, NJ, pp. 203–225.

Peterson, S.E., Kulhavy, R.W., Stock, W.A., Pridemore, D.R., 1991. How map features cue associated verbal content. Bulletin of the Psychonomic Society 29, 158–160.

Roscoe, S.N., 1968. Airborne displays for flight and navigation. Human Factors 10, 321–332.

Sanchez, C.A., Wiley, J., 2006. An examination of the seductive details effect in terms of working memory capacity. Memory and Cognition 34 (2), 344–355.

Schwartz, N.H., Kulhavy, R.W., 1981. Map features and recall of discourse. Contemporary Educational Psychology 6, 151–158.

Sholl, M.J., Egeth, H.E., 1982. Cognitive correlates of map-reading ability. Intelligence 6, 215–230.

Sloutsky, V.M., Kaminski, J.A., Heckler, A., 2005. The advantage of simple symbols for learning and transfer. Psychonomic Bulletin and Review 12 (3), 508–513.

Stumpf, H., Eliot, J., 1995. Gender-related differences in spatial ability and the *k* factor of general spatial ability in a population of academically talented students. Personality and Individual Differences 19, 33–45.

Tufte, E., 2001. The Visual Display of Quantitative Information. Graphics Press, Cheshire, 1983.

Tullis, T.S., 1983. The formatting of alphanumeric displays. Human Factors 25 (6), 657–682.

Tversky, B., Morrison, J.B., Betrancourt, M., 2002. Animation: can it facilitate? International Journal of Human–Computer Studies 57 (4), 247–262.

Uttal, D.H., 2000. Seeing the big picture: Map use and the development of spatial cognition. Developmental Science 3, 247–286.

Verdi, M.P., Kulhavy, R.W., 2002. Learning with maps and texts: an overview. Educational Psychology Review 14 (1), 27–46.

Zacks, J., Levy, E., Tversky, B., Schiano, D.J., 1998. Reading bar graphs: effects of extraneous depth cues and graphical context. Journal of Experimental Psychology: Applied 4, 119–138.

Zacks, J.M., Mires, J., Tversky, B., Hazeltine, E., 2002. Mental spatial transformations of objects and perspective. Spatial Cognition & Computation 2, 315–322.