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The impact of visual information on perceptions of water resource problems and management alternatives

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To assess changes in human understanding and decision making, the paper examines (1) the influence of visual information on perceptions about groundwater management in Phoenix, Arizona and (2) the correlates and dimensions underlying people's views about water scarcity and mitigation strategies. While perceptions entrenched in ideologies are difficult to change, different types of information (three-dimensional versus two-dimensional) have distinct impacts on the perceived magnitude of problems compared to judgements about their causes and solutions. Overall, visual information may be especially useful for developing a shared understanding of problems and a collective vision for management alternatives. Additional implications of this study for fostering environmental awareness, policy support, and collaborative decision making are also discussed.

Keywords: water resource planning; environmental perception; risk communication; information visualisation; public participation

1. Introduction

Providing an adequate supply of safe, reliable water in the face of rising demands is a salient issue worldwide. Sustainable water management is especially challenging in rapidly growing arid cities, where the over-extraction of non-renewable groundwater is a central concern. In Arizona, for example, the overuse of groundwater in the 1970s was so extensive that the region's aquifers would be drained within a hundred years (Glennon 1991). Groundwater overdraft, or withdrawing water at rates that exceed natural or artificial replenishment, creates problems such as aquifer depletion, land subsidence, and stream degradation (Larson *et al*. 2009). To address overdraft, Arizona adopted the 1980 Groundwater Management Act (GMA) and, therein, the goal of 'safe yield' of groundwater by 2025. The state enacted the GMA only after the Carter administration stipulated that overdraft problems must be addressed to receive federal funding for the Central Arizona Project (CAP) (Connall 1982). The CAP canal now delivers 1.5 million acre-feet of Colorado River water to the region (CAP 2008). Yet groundwater problems persist, and planning initiatives are

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underway to address them. Regional planning efforts, for example, have recently aimed to understand and mitigate cone of depression problems in the East Valley of metropolitan Phoenix, in part through collaborative modelling of groundwater flows (East Valley Water Forum 2007).

Given the unseen and elusive nature of aquifers beneath the earth's surface, visual information may be especially useful for groundwater management. Hydrologic modelling is common in water resources research and planning, with decision applications ranging from the operation of reservoir levels to the determination of minimum stream flows for endangered fish (Reitsma 1996, Simonovic 1996, Nyerges *et al*. 2006). Such visual information technologies possess special potential because of the power of vision to aid problem-solving (McCormick *et al*. 1987, Medyckyj-Scott 1994). Potential benefits include establishing a shared understanding of problems, evaluating management alternatives and engaging stakeholders in decision making (Carver *et al*. 1995, Lovejoy *et al*. 1997, Zigurs *et al*. 1999). Yet human factors may inhibit their effectiveness, thereby justifying social science research on the utility and impact of visual information technologies.

This paper evaluates the effects of visual information technology on public understanding of groundwater issues in the desert metropolis of Phoenix, Arizona. The primary research question is: how does visual information influence perceptions about the magnitude of water resource problems, their causes and possible solutions? Specifically, the study compares a three-dimensional (3D) demonstration in a semi-immersive virtual environment to a parallel two-dimensional (2D) PowerPoint presentation in a standard meeting room. In order to understand changes in human understanding, moreover, theoretical correlates for the perceived magnitude of risks are evaluated as well as the cognitive dimensions underlying the perceived causes of water shortages and the perceived effectiveness of mitigation strategies. Since social values and cultural factors are key elements of water disputes and resource management (Cai *et al*. 2004), our study focuses on the socio-cultural beliefs that underlie perceptions and potentially influence their malleability.

Given the rising applications of computer technology and barriers to their utility for decision making (Carver *et al*. 1995, Reitsma *et al*. 1996), research is needed to comprehend how the ensuing information influences human understanding of resource problems and management alternatives (Medyckyj-Scott 1994, Gershon and Eick 1997, Nyerges *et al*. 2006). Advancing knowledge about perceptions and how they change in relation to different types of information is central to effective education and communication (Slovic *et al*. 1991, Wakefield and Elliot 2003). By addressing public perceptions, studies such as this one can aid in reducing conflicts among divergent interests while facilitating participatory decision making and enhancing co-operative environmental management (Ozawa 1996).

2. Risk perceptions and human understanding

As a component of human cognition, perceptions can be thought of as how people recall things through acquiring, interpreting, selecting and organising sensory information (Lindsay and Norman 1977, Golledge and Stimson 1997). Because they depend on how sensory stimuli are filtered and interpreted in the mind, people's perceptions of risks are variable and often differ from expert risk assessments (Slovic 1987, McDaniels *et al*. 1997). Although knowledge of risks may influence perceptions, rational information-based judgements are confounded by psychological and social factors (Leiserowitz 2005). Biased media reports and issue framing, for example, significantly affect perceptions of environmental risks (Slovic *et al.* 1991).

Scholars emphasise the social construction of risk wherein judgements depend on multiple factors including socio-cultural context (Wakefield and Elliot 2003, Leiserowitz 2006). Prior research has focused extensively on how particular characteristics of risks, such as their dreadfulness and controllability, determine people's perceptions, while much less research has examined how judgements vary among people with different social characteristics (Willis *et al.* 2005). Prominent scholars suggest that plural cultural rationalities, or different ways of knowing based on ecological, social and political beliefs, critically influence perceptions (Schwarz and Thompson 1990, Stern *et al.* 1995, Leiserowitz 2006). Since judgements entrenched in value-based ideologies tend to be steadfast and unchanging (Gilbert *et al.* 1998), this paper focuses on how socio-cultural beliefs influence perceptions before and after exposure to visual information.

Worldviews, or basic beliefs shared by social groups, form the foundation for specific judgements about the environment (Stern *et al.* 1995, Stern 2000). A biocentric worldview, for example, leads to heightened concerns about ecological risks. The Dominant Social Paradigm (DSP) of thought, stressing anthropocentric interests, limitless growth and technological solutions to societal problems, is often contrasted with the New Ecological Paradigm (NEP). These opposing worldviews are typically evaluated with the NEP scale of measurement, which is a series of agree–disagree statements about human-ecological relations (Dunlap *et al.* 2000). Through reliability and factor analyses, previous studies have confirmed the internal consistency of the NEP scale and three dimensions of worldviews: the *fragile balance of nature* and *limits to growth* (pro-ecological) and *human domination of the earth* (anti-ecological) (Dunlap *et al.* 2000). These perspectives are seen in classic arguments about population growth and human ingenuity, which respectively reflect ecological pessimism in the face of resource limits and technological optimism in recognition of human control over nature.

Basic political beliefs, often conceptualised in the US as a conservative to liberal continuum, similarly influence judgements about risks and appropriate mitigation strategies (Fitchen 1987, Sjoberg 2002). Whereas conservatives tend to favour individualism and oppose government intervention in the economy or private property, liberals favour social equality and are more supportive of government efforts to protect the public good. Cultural worldviews, which are commonly understood by scholars as value-based orientations toward top-down regulation versus bottom-up strategies (on a 'grid' axis) and social versus individualistic leanings (on a 'group' axis), affect judgements about hierarchical management strategies, organised co-operative efforts, free-market mechanisms, or 'do nothing' approaches (Schwarz and Thompson 1990). The beliefs embodied in cultural perspectives filter information in ways that affect judgements about environmental risks, their sources and management alternatives (Ellis and Thompson 1997, Lima and Castro 2005). In a study about global warming, for example, Leiserowitz (2005) illustrated that liberal 'alarmists' who view the earth as fragile demand public action to address detrimental impacts, while conservative 'naysayers' who deny human-induced climate changes and attribute warming to natural processes support a 'do nothing' policy approach.

For the purposes of this study, perceptions of water resource issues were examined concerning: (1) the magnitude of groundwater problems; (2) the degree to which various factors contribute to water scarcity; and, (3) the effectiveness of different management strategies. Judgements are likely to be distinguished by natural versus anthropogenic causes and voluntary versus regulatory solutions. In addition, biocentric worldviews and liberal political orientations will likely lead to greater perceived severity of the problems, while the perceptual judgements most engrained in ideological beliefs would be most resolute. In the next section, the ways in which the type of visual information might differently influence judgements about water problems and their management are discussed.

3. Visual information technology and human understanding

Visual information has the potential to facilitate understanding and decision making about complex environmental problems, which are often plagued by conflicting interests (MacEachren and Brewer 2004). Three-dimensional visual settings are especially useful for acquiring spatial knowledge about the world because they mimic physical interaction in realistic ways (Koh *et al.* 1999, Durlach *et al.* 2000). Evidence indicates, however, that photo-realism and immersion are limited in their effectiveness. Mak *et al.* (2005) concluded that simplified 2D visuals were less complicated and time-consuming for the average user to interpret compared to 3D representations of environmental impacts. Despite the visual appeal of 3D images, similar findings have been reported elsewhere in that people have more accurately extracted information from simple 2D graphs (Fisher *et al.* 1997).

The effectiveness of information technology is dependent not only on the visual design of presentations but also the viewers' cognitive abilities, personal characteristics, and user experiences (Nielsen 1993, Shniederman 1998). Because knowledgeable professionals are comfortable with domain-specific representations, for example, they may be resistant to new types of information (Block 2007). Generally, information technology provides a 'frame of reference' within which participants can share visual objects (such as maps and graphics) to discuss and co-ordinate perspectives (MacEachren and Brewer 2004, p. 12). As such, visual information technology helps to focus attention on particular issues, establish a collective understanding of problems, and engage and empower stakeholders to explore management alternatives (Reitsma *et al.* 1996, Zigurs *et al.* 1999). Further research is needed, however, to validate these claims and more fully understand how different informational representations can best realise these benefits (Simonovic and Bender 1996).

Because emotional reactions often determine judgements about risk, vivid (colourful, immersive, dynamic) displays may influence perceptions more so than technical (statistical, scientific) displays (Leiserowitz 2006). Leiserowitz (2004) found that the movie *The Day After Tomorrow* altered viewers' perceptions about climate change despite its fictional plot. Yet additional research should test the impacts of various types of visual information on environmental understanding and decision making. In the present study, the semi-immersive 3D setting may lead to greater changes in perceptions than the traditional 2D setting, due to the multidimensional depiction of groundwater issues and affective responses to the vivid displays of the high-technology setting. At the same time, the relatively familiar and simple 2D information might better aid understanding about the nature and severity of groundwater overdraft than the complex 3D depictions.

4. Research design

Prominent researchers describe an array of appropriate methods for social and behavioural studies of information technologies, from purely experimental designs to in-the-field approaches (Nyerges *et al*. 2002). A quasi-experimental approach was employed (Bryman 2001) that lacked full control of visual design elements and random assignment to the 3D and 2D groups, as described further below. By examining changes in perceptions before and after exposure to visual information, written surveys measured diverse judgements in relation to a 3D demonstration in Arizona State University's (ASU) Decision Theater (DT) and a parallel 2D PowerPoint presentation in a standard classroom.

4.1. The visual information settings

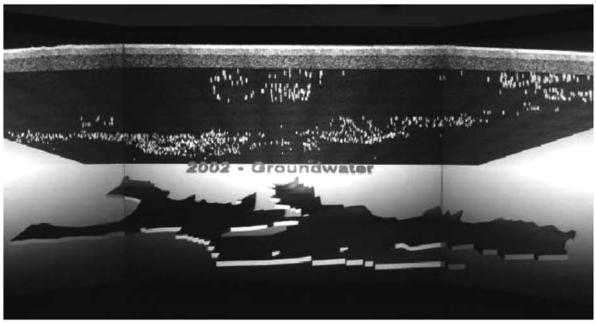
For the 3D presentation, the study used an existing groundwater demonstration created in 2005 for the grand opening of the Decision Theater. The DT is a semi-immersive visualisation environment featuring animated graphics that surround viewers on high-resolution large-screen displays. On seven walls of the 10-sided room are 10 × 8 foot screens capable of rendering computer displays in stereo, with three-dimensional viewing through polarised stereo '3D' glasses. The visual images in the DT primarily portrayed physical depth to the underground aquifer. Images on a peripheral screen – the 'digital dashboard' – consisted of a series of small supplemental graphs and legends to guide the presenter.

For the 2D setting, visual images in PowerPoint were designed to replicate the DT imagery as closely as possible (see Figure 1). Where two large images moved across the DT's multiple screens, the still images were captured and presented side-by-side in a PowerPoint slide to support a similar comparison. For the PowerPoint presentation, small dashboard images were in the lower corner of the slides. Although the 2D presentations included 2.5D images (Figure 1b), stereo glasses and the large multiple screen environment of the DT were not used in the 2D setting. The 2D presentation, projected on a standard classroom screen, included smaller images in a narrower field of vision. The same person narrated, live, both presentations from a standard script.

The 10-minute presentations addressed excessive groundwater withdrawals in the region while illustrating water levels and flows to pinpoint cone of depression problems. The illustrations depicted spatially referenced images of water table depths with an undulating surface and arrows indicating flows from high to low levels (where cones of depression occurred) in 1983 and 2002. Another image showed the location of water infrastructure, such as canals and wells, in relation to an aerial image draped over a digital elevation model depicting land uses and above-ground topography. The verbal presentation and 'digital dashboard' images emphasised the passing of the GMA policy in 1980 and completion of the CAP canal for delivery of Colorado River water to the region. Along with the conversion of farms into less water-intensive urban land uses, these factors were associated with a decline in groundwater overdraft and a corresponding reduction in cones of depression over time.

While focusing on particular aspects of water problems, the presentations did not highlight all of the pertinent issues involved with groundwater overdraft and resource management. For example, the costs and negative impacts of transferring water from agricultural uses and the Colorado River for continued urban

a. Example"3D" Image in the DT (photo taken by Jessica Block)



b. Parallel "2D" PowerPoint Slide

c. Example "digital dashboard" images

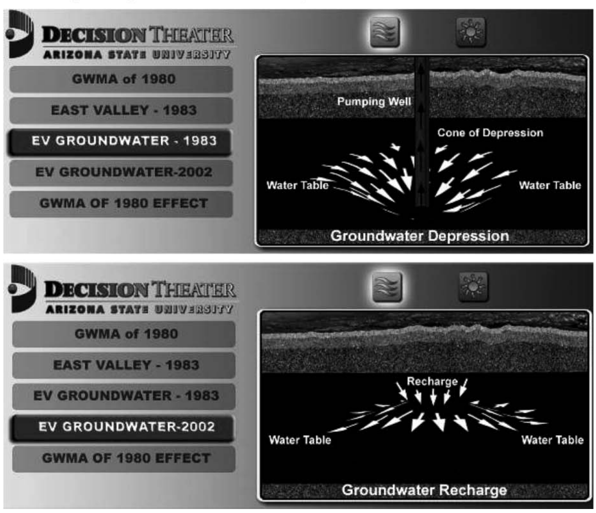


Figure 1. Visual depictions of groundwater levels from the presentations. Three-dimensional viewing in the Decision Theater (DT) was enhanced with polarized stereo '3D' glasses. The 'digital dashboard' guides (examples in 1c) at the bottom of the PowerPoint slides (1b) appear on a far right screen in the DT and therefore are not seen in 1a above.

development were not addressed. Furthermore, the presentations narrowly stressed positive improvements in groundwater management despite remaining overdraft problems. Overall, although the quasi-experimental study lacked full control over the specific content and design elements of the visual information presented, the results are still informative given the similar script and graphics across the 3D and 2D settings.

4.2. The sample and surveys

A targeted, convenience sample of ASU undergraduate students participated in this study, which is common in perception research (see, for example, McDaniels *et al.* 1995). First, students were directed via email to complete an online (pre-presentation) survey with questions about their risk perceptions and socio-cultural beliefs. At the end of the web survey, each student selected among a group of times, about a week or two later, during which they could participate in the second half of the experiment involving the presentation and a hard-copy follow-up survey with the same perception questions, and basic demographic information. Unknown to the participants, some of the times were for the 3D presentation, while others were for the 2D presentation. A purely random approach to group assignments was not possible due to the difficulty of scheduling students in the DT. Rather than strictly treating the 2D as a control, therefore, the quasi-experimental findings are described comparatively in terms of the changes in perceptions that occurred for each setting.

A total of 76 students attended the presentations and completed the surveys ($n = 35$ for 3D, $n = 41$ for 2D). Participants' age ranged from 18–46, with a mean of 22 years. Respondents reportedly had lived in the Phoenix area for less than one year to 30 years (mean was 9.2 years, with a standard deviation of 8.49). Approximately three-quarters were Anglo, 13% were Hispanic and 10% Asian. More males (67%) participated than females. Generalising the findings to other populations is limited because of the narrow sample.

4.3. The survey data and analyses

The primary dependent variables of interest represent perceptions concerning the magnitude of water resource problems and the causes of and solutions to water shortages. Participants answered survey questions on five-point ordinal response scales. Multi-item closed-ended questions asked:

(1) How big a problem do you think each issue [water shortages/groundwater overdraft] currently is in the greater Phoenix area? (small to big) (see Figure 2).
(2) How much do you think the following contribute to water shortages in the Phoenix area? (not at all to a lot) (see Figure 3a and Table 1 for the six options listed).
(3) How effective do you think the following steps are for preventing water shortages in the Phoenix area? (not to very) (see Figure 3b and Table 1 for the six options listed).

This core set of questions measuring perceptions appeared in the same manner on the pre- and post-presentation surveys (see Table 1 for descriptive statistics). The

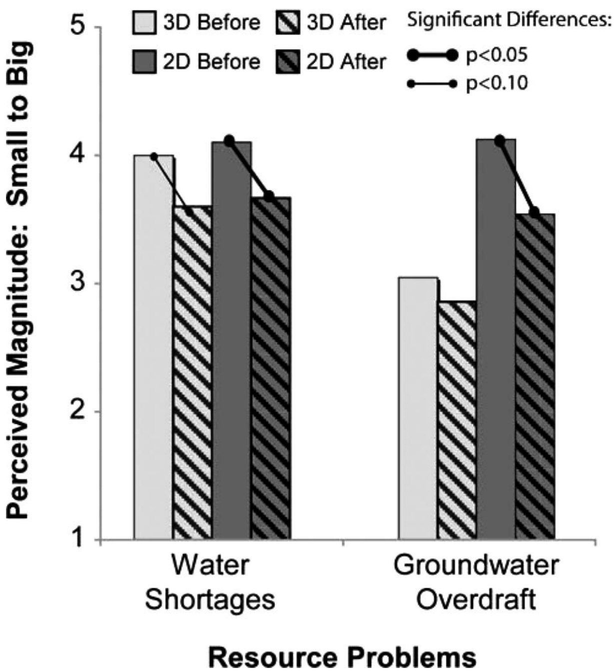


Figure 2. Changes in the perceived magnitude of water risks before and after the 3D and 2D visual information.

causes and solutions listed in the surveys were selected based on a pilot exercise with other students, who were asked the same questions in an open-ended format. From the common responses, causes and solutions were intentionally included that were and were not stressed in the presentations (as indicated in Table 1 and Figure 3). Non-parametric statistics (paired Wilcoxon tests) examined changes in perceptions before and after the presentations for the 3D and 2D groups separately.

For the correlation analysis of explanatory variables, the individual evaluations of water shortages and groundwater overdraft (question (1) above) were combined as a reliable composite measure of the perceived magnitude of resource problems (Cronbach's alpha = 0.83), such that high values correspond to severe risks. Cronbach's alpha is a common statistical test of reliability, or internal consistency, with a standard criterion of 0.7 or higher and a minimum of 0.5 deemed acceptable for research (Nunnally 1967). Spearman's rho coefficients examined the correlations between the perceived magnitude of water risks and the explanatory variables, for which individuals' average responses were also calculated for greater statistical reliability.

Three groups of explanatory factors were evaluated in relation to the perceived magnitude of water resource problems: domain-specific knowledge, ecological worldviews and political ideologies (see descriptive statistics and correlations in Table 2). Knowledge was measured by self-report on a five-point scale anchored by 'not' and 'very' knowledgeable, with a question asking how familiar or knowledgeable respondents are about water resources, groundwater overdraft and cones of

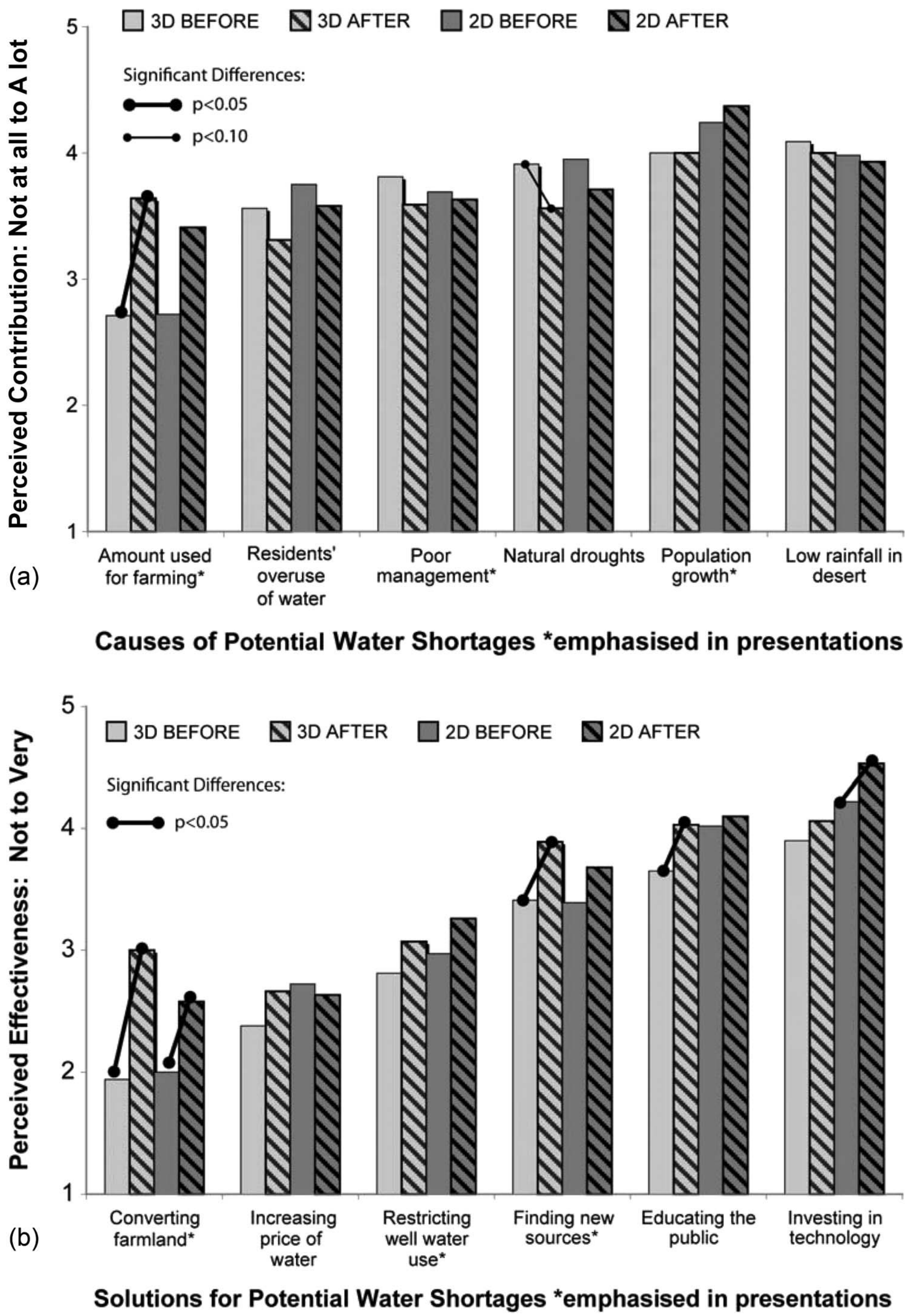


Figure 3. Changes in risk perceptions following the 3D and 2D visual information. (a) Perceived causes of potential 'water shortages'. (b) Perceived effectiveness of mitigation strategies.

Table 1. Descriptive statistics for perceptions about water scarcity before and after visual information.

Dependent variables: perceptions	Mean (St. dev.) Before	Mean (St. dev.) After	Valid N (before)*
Magnitude of risks (5 = big problem)			
Water shortages	4.06 (1.09)	3.66 (1.56)	71
Groundwater overdraft	3.57 (1.26)	3.23 (1.00)	46
Causes of water scarcity (5 = contributes a lot)			
Population growth	4.13 (0.91)	4.20 (0.88)	75
Low rainfall in desert	4.03 (1.03)	3.96 (0.92)	74
Naturally occurring drought	3.93 (0.97)	3.64 (1.06)	74
Poor management of water	3.74 (1.13)	3.63 (1.05)	70
Residents' overuse of water	3.66 (1.10)	3.46 (0.97)	74
Amount of water used for faming	2.93 (1.03)	3.51 (1.15)	69
Approaches to resource management (5 = very effective)			
Investing in new technology	4.08 (0.96)	4.31 (0.84)	72
Educating the public about conserving	3.85 (1.01)	4.07 (0.94)	75
Finding new water sources	3.40 (1.22)	3.78 (1.04)	75
Restricting use of water from wells	2.90 (1.06)	3.17 (0.96)	63
Increasing the price of water	2.56 (1.23)	2.64 (1.24)	73
Converting farmland to residences	1.97 (1.01)	2.77 (1.22)	70

Notes: Italics highlights those issues emphasized in the presentations. Descriptive statistics presented for entire sample, with 3D and 2D groups combined (see Figures 1–3 for 3D vs. 2D differences and for changes in judgements following visual information).

*Valid N for all post-information ('after') judgements was 70 or greater, except for the perceived effectiveness of restricting wells (n = 63).

depression. The three measures comprise an overall index of knowledge (alpha = 0.67). Ecological worldviews were measured with six NEP statements, which were examined individually and as a composite index (alpha = 0.65). Following previous research and factor analyses, two sub-dimensions of ecological worldviews were evaluated to represent basic beliefs about human control over nature (alpha = 0.59) and the fragility of the earth (alpha = 0.55). Finally, two statements evaluated political beliefs regarding the free market economy and private property rights. Together, these variables represent political ideology (alpha = 0.69), with high values indicating conservative beliefs.

Next, the underlying dimensions of judgements about the causes and solutions for 'water shortages' were examined (questions (2) and (3) above) using factor analysis (see Table 3 for dimensions and loadings). As a common technique favoured for producing clear factors (Kim and Mueller 1978), principal components extraction with varimax rotation was employed. Eigenvalues of 1 or greater indicated significant factors, and loadings of 0.5 or higher identified associated causes and solutions (Carmines and Zeller 1979).

Correlation and factor analyses were conducted on the combined (3D and 2D) sample for greater statistical reliability in understanding the ideological basis of perceptions. Both analyses were conducted on pre- and post-presentation perceptions. The results presented include judgements before and after the presentations to assess changes in the dimensions of perceptions and the influence of explanatory factors on human understanding.

5. Empirical findings

First, the correlates of perceived risk magnitude are presented, followed by the factor analyses for the perceived causes and solutions. Next, the results illustrating how the various judgements changed comparatively across the 3D and 2D presentations are presented. The significant correlates and statistical differences are reported based on the standard $p < 0.05$ level.

5.1. Correlates for the perceived magnitude of risks

The factors explaining risk perceptions (see Spearman's rho values in Table 2) shed light on the observed changes in perceptions. Prior knowledge, particularly awareness of water issues generally, was significant in explaining risk perceptions. Specifically, *greater* knowledge was associated with the perceived *severity* of problems. General knowledge (before the presentations) was the only factor that explained additional variation in perceptions following the visual information, indicating that common information may lead to a shared understanding about specific issues (such as cones of depression) while also possibly heightening the influence of broader knowledge on judgements. Compared to knowledge, the other

Table 2. Correlates of the perceived magnitude of water risks before and after visual information presentations.

Explanatory variables	Descriptive statistics				Spearman's Rho	
	Mean	Median	Std. dev.	N	Before	After
Knowledge: index of 3	*2.23*	*2.3*	*0.783*	*75*	*0.208**	*0.261***
Water resources	3.01	3	0.979	75	0.215*	**0.276****
Groundwater overdraft	2.01	2	1.059	75	0.149	0.185
Cone of depression	1.67	1	0.977	75	0.041	0.061
*Pro-ecological worldview: index of 6^*	*3.37*	*3.3*	*0.707*	*75*	*0.353****	*0.232***
Fragile Earth: index of 3	3.59	3.7	0.883	75	0.289**	0.16
Humans are abusing environment	3.85	4	1.062	75	0.351***	0.197*
Balance of nature is delicate	3.58	4	1.322	73	0.183	0.039
We're approaching earth's limits	3.3	3	1.202	66	0.129	0.097
Humans dominate: index of 3	2.84	3	0.898	75	−0.282**	−0.223*
Earth has plenty of natural resources	3.05	3	1.344	74	−0.149	−0.104
Humans have right to modify environment	2.96	3	1.152	74	−0.331***	−**0.308*****
We will be able to control nature	2.48	4	1.208	69	−0.137	−0.079
Political orientation: index of 2	*2.56*	*3.5*	*1.127*	*75*	*−0.436****	*−0.274***
Government should not interfere with free market	2.74	3	1.334	68	−**0.530*****	−**0.356*****
Property owners should be able to do whatever	2.42	4	1.25	74	−0.184	−0.149

Notes: All variables measured on 5-point scales, where 5 = 'very knowledgeable' and 'strongly agree'. Rho value significant at $p < 0.01$***, 0.05**, and 0.10* levels, with most influential correlates in bold for emphasis.

^For the omnibus NEP index, variable is coded such that 5 = pro-ecological (fragile earth variables = agree and human dominate variables = disagree).

theoretical predictors – that is, socio-cultural beliefs – were more critical in explaining perceptions.

Ecological worldviews were correlated with the perceived magnitude of resource problems both before and after the presentations, although more so prior to the visual information. This suggests broad-based beliefs about the environment might be overcome in developing a shared understanding of specific resource problems and their mitigation, although some beliefs did remain critically important. The most significant ecological beliefs pertained to the degree of human impact on the environment and the rights of people to modify nature. After the presentations, the belief in human control over nature was the second most important factor explaining risk perceptions, thereby potentially affecting views about appropriate resource uses and management strategies (e.g. technological solutions such as cloud-seeding to enhance precipitation).

Finally, perceptions about water resource problems were best explained by political ideologies, both before and after the presentations. Belief in the free-market economy, above all, was negatively correlated with the perceived magnitude of water risks. As a whole, the influence of political ideologies was steadfast in explaining perceptions, whereas the significance of ecological worldviews diminished and general water knowledge rose following the specific visual information about groundwater overdraft.

5.2. *Cognitive dimensions of perceived risks*

As expected, the factor analysis distinguished two dominant dimensions in perceptions about the causes of water shortages (see loadings in Table 3): natural factors (drought and aridity) and anthropogenic sources (management, growth and residential uses). A third dimension of perceptions highlighted agricultural uses of water as a distinct factor contributing to water shortages. Following the presentations (see superscripts and notes in Table 3), the ideological dimensions underlying the perceived contributors to risks largely remained the same, except that judgements about agricultural water use (a primary focus of the presentations) was no longer a distinct dimension. Instead, it was newly associated with both natural and anthropogenic causes (though the loadings were weak at <0.5). These findings highlight an enduring tendency to distinctively blame nature *or* people for resource problems.

Regarding management strategies, the factor analysis distinguished perceptions toward top-down organised measures involving regulations or economic investments (see first factor in Table 3). A second factor represented judgements toward voluntary approaches such as conservation education. A third factor again highlighted agricultural interests as a distinct realm of judgement. After viewing the visual information, perceptions about the conversion of agricultural land again changed and were subsequently linked to stringent restrictions and pricing mechanisms, which was otherwise a persistent dimension of perceptions. Meanwhile, finding new sources of water (emphasised in the presentations) uniquely dominated a second factor, and conservation through technology and education (not emphasised in the presentations) comprised a third factor. This change may reflect the ability of visual information to influence perceptions about management strategies more so than the causes of problems, a point further discussed in the patterns of changes in individual judgements below.

Table 3. Factor loadings for dimensions of perceptions and summary of changes in judgements following visual information.

Risk perception judgements	Rotated factor matrix (Variance explained)			Changes in perceptions	
Causes of water shortages	1 (30%)	2 (26%)	3 (19%)	3D	2D
Poor management of water[1]	0.858			none	none
Population growth[1]	0.796			none	none
Residents' overuse of water[1]	0.646			none	none
Amount of water used for farming[1, 2]ˆ			0.956ˆ	***greater*	none
Naturally occurring drought[2]		0.841		**lesser*	none
Low rainfall in desert[2]		0.867		none	none
Solutions to water shortages	1 (30%)	2 (23%)	3 (19%)	3D	2D
Converting farmland to residences[1]			0.924ˆ	***greater*	***greater*
Increasing the price of water[1]	0.849			none	none
Restricting use of water from wells[1]	0.774			none	none
Investing in low water use technology[3]	0.617ˆ			none	***greater*
Educating the public about conserving[3]		0.672ˆ		***greater*	none
Finding new sources of water[2]		0.83		***greater*	none

Notes: Italics highlight those issues emphasised in the presentations. Factor loadings >0.5 are reported. Superscripts indicate the variables loading onto post-presentation factors (1, 2, and in some cases, 3), with a caretˆ indicating those perceptions associated with a different factor following the visual information. For example, perceptions about water use for farming ^loaded onto factors 1 and 2 after the presentations, instead of loading onto its own factor (3) as it did prior to the visual information.

5.3. Changes in perceptions: 3D versus 2D

Both resource problems – water shortages and groundwater overdraft – were seen as less severe after both presentations, although the changes were more significant for the 2D group (see Figure 2). Interpreting the changes in perceptions concerning overdraft is problematic because the valid sample sizes were small due to 'don't know' responses before the presentations and because the two groups differed in their *a priori* judgements. While the 2D group perceived overdraft as a bigger problem than the 3D group beforehand, the altered perceptions resulted in relatively similar views between the two groups after the visual information. Regardless, the Wilcoxon tests of differences for overall perceptions (i.e. the composite index) of water resource problems indicate changes in perceptions following the 2D information ($p = 0.002$, n = 39), but not the 3D information ($p = 0.119$, n = 33).

The only significant change in perceptions about the causes of water shortages was for the 3D group, which viewed the amount of water used for farming as a larger contributor after the visual information (Figure 3a). Perceptions about the other two issues emphasised – water management and population growth – did not change significantly after either demonstration, perhaps because these factors were positively portrayed as minimising groundwater overdraft through resource policies and the conversion of farmland into residential homes. Water use for farming was the only factor that was seen as a *bigger* contributor to potential water shortages following the presentations, with the exception of a slight (insignificant) increase in population growth for the 2D group.

Perceptions about the effectiveness of management alternatives changed more than the perceived causes of water scarcity, especially for the 3D setting (Figure 3).

Both presentations led to significant increases in the perceived effectiveness of converting agriculture to urban land uses. For the 3D group, judgements about finding new sources of water (emphasised) and educating the public about conservation (not emphasised) uniquely increased, while for the 2D presentation, those about investing in conservation technology (not emphasised) increased. The only management alternative not seen as more effective following the visual information was increasing the price of water, which slightly decreased for the 2D group (although the change was not statistically significant).

6. Discussion of results

In summary, the factor analysis illustrates how particular dimensions of people's judgements remain unchanged, particularly perceptions about natural and anthropogenic causes of resource problems and the effectiveness of top-down regulatory strategies to water management. At the same time, perceptions about agricultural uses of water – a central focus in the visual information presentations – were most malleable. Overall, the perceived magnitude of risks changed more for the 2D than the 3D setting, while the opposite was found for perceptions about the causes and solutions to water resource risks. These findings suggest that different types of information may be more or less effective at changing particular realms of human understanding and judgement.

Recognising the limitations of this study, the authors are cautious not to over-extend the results to the broader public or to attribute the different impacts of the two visual informational settings to a single element, such as dimensionality (3D versus 2D) or animation. Instead, emphasis is placed on interpreting the results relative to theory and previous studies (as described earlier) while highlighting the practical implications of our results as well as critical areas for future research. Additional research with a broader population and sample, for example, could address how human understanding and perceptions vary and change in response to visual information based on age and tenure of residency, since these factors might influence knowledge and judgements about local risks.

Pre-exiting knowledge about complicated environmental issues appears to be an important determinant of risk perceptions, even in the face of specific visual information. While such information led to a common understanding of specific issues (such as groundwater overdraft) in this study, broader knowledge of water issues was more significant in explaining perceptions after exposure to the visual information. Although focus on specific issues such as groundwater overdraft may assist in narrowing attention to particular problems, efforts to educate the broad public, foster communication among diverse stakeholders, or facilitate group decision making may be complicated by different levels of *a priori* knowledge and experience among participants. Public outreach and involvement processes should therefore be structured to both focus on critical aspects of resource management (such as the growing importance of residential water uses as agricultural land is being converted) while also addressing divergent knowledge levels among the participants involved. Furthermore, research is warranted on how different types of knowledge – whether based in scientific training, local and professional experiences, or cultural ways of knowing – influence perceptions as well as the ability of visual information to alter understanding and decision making among diverse stakeholders. Considering socio-cultural values and beliefs is just as critical as considering technical knowledge and awareness of resource issues, if not more so, since attempts to facilitate mutually agreeable solutions might be hindered by stakeholders perpetually defending ideological positions (Leach and Pelkey 2001).

Influential socio-cultural beliefs render some perceptions of water resource issues especially difficult to change, since the core values underlying such beliefs typically develop early in life and are steadfast throughout. Perceptions in this study reflected ecological worldviews in that persistent judgements were distinguished by blaming water shortages on nature versus anthropogenic causes. Moreover, perceptions of effective management strategies aligned with cultural beliefs in hierarchical regulatory approaches versus collective voluntary efforts. While these dimensions of judgements remained significant following the visual information, distinctive views about agriculture diminished and shifted most substantially as a result of narrowing participants' attention to the impact of irrigated farming on groundwater overdraft problems. Altogether, the changes in perceptions capture the framing and focusing effects of visual information, especially in terms of judgements about agriculture. However, prudence must be employed in generalising this result since past research has found diverging perceptions among urban and rural residents (McDaniels *et al.* 1997). Because urban-rural conflicts are pervasive in water management, partly due to ideological differences across geographic communities, views about agriculture as the source of (or solution to) resource problems may not be as malleable as the findings indicate for different populations or areas. For example, the framing of issues around urban development of farmland or the transfer of water from agriculture to urban uses in other cases may serve to heighten opposing interests rather than ameliorating them.

In general, as a shared understanding emerges in response to common information, steadfast ideologies and cultural values may come to the forefront in collaborative decision making or conflict resolution settings. Since ecological worldviews were not as persistent as political beliefs (specifically about the free-market economy) in explaining risk perceptions, broad-based beliefs about the environment might be overcome while those about the appropriate institutions for governing resource use and management may become more problematic. These findings underscore the importance of structuring outreach and decision processes not only to address technical knowledge of resource problems, but also to consider mutual acceptance of diverse socio-cultural values and interests, which ultimately have a strong influence on judgements about risks and their mitigation. Since judgements about the causes of problems and regulatory approaches were relatively unfaltering (due to the persistence of the underlying values that influence them), the use of visual information may be most effectively aimed at shifting understanding of particular risks and their impacts as well as the full range of management alternatives (including voluntary or collective measures) and their effectiveness.

With respect to media type, the two-dimensional demonstration may have had a greater impact on the perceived magnitude of risks than the three-dimensional setting because of the relatively familiar and simple visual depictions of groundwater overdraft (for example, see the images in Figure 1c depicting the shift from overdraft to recharge). The simple digital dashboard images – readily visible in the small-screen setting of the 2D PowerPoint slide compared to the 3D surround-screen environment – might better convey groundwater issues compared to the three-dimensional depictions. This explanation (regarding the simplicity and familiarity of images) is consistent with past reports that realism and 3D visuals are not necessarily the most useful in conveying technical information and improving understanding of multidimensional phenomena. Yet the results also suggest that different types of information may differentially impact distinctive judgements, specifically in the 3D visual information had a slightly greater effect on both the perceived causes of risk as well as the effectiveness of solutions for risk mitigation. These differences are perhaps due to affective, optimistic responses in the high-technology setting of the Decision Theater, since vivid information may have a greater impact on perceptions than concrete technical information (Leiserowitz 2006). Thus, planners and decision makers should carefully consider the goals of outreach, public involvement and educational endeavours in choosing the type of information employed and its demonstrated effectiveness for changing perceptions, understanding and decision making in particular ways.

As a whole, this study advances knowledge about how visual information technology influences human understanding of water resource problems and their management, specifically in light of the socio-cultural determinants of judgements. Although the findings are limited, incorporating visual information in decision making appears particularly useful for fostering a shared understanding of technical problems, focusing people on particular issues, and exploring various approaches to risk mitigation. Yet challenges to changing entrenched ideological views remain and the impacts of different types of information are complex, necessitating further research across diverse populations, risks, informational settings and decision contexts. In the future, studies should also address (1) how different visual information influences human understanding in terms of a variety of judgements and perspectives on multifaceted environmental issues, and (2) how the impacts differ across diverse risks and among stakeholders with varying knowledge, experience and socio-cultural orientations and characteristics. Answering these questions will necessitate methodological approaches ranging from highly controlled experiments that carefully alter elements of information displays to qualitatively rich case studies that further knowledge about how visual information technology influences people's views in a diversity of real-world decision settings. Additional social science research in these arenas is essential for comprehending human responses and interactions with visual information technology and for fully realising its potential for water resource management and environmental decision making.

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