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Debunking Sustainability Excuses with Instrumentality and Expectancy Visualizations: A Physiological Perspective

Zhiyin Li
Nanyang Technological University, zhiyinli@cityu.edu.hk

Ben Choi
Nanyang Technological University, benchoi@ntu.edu.sg

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Completed Research Paper

Zhiyin LI
City University of Hong Kong
83 Tat Chee Ave, Hong Kong
zhiyinli@cityu.edu.hk

Ben CHOI
Nanyang Technological University
52 Nanyang Ave, Singapore
benchoi@ntu.edu.sg

Abstract

This study advances the IS literature by investigating the effects of visualization on promoting sustainability knowledge and pro-environmental behaviors. Specifically, drawing on the visualization literature, we explain how the key visualization features, expectancy illustration, and interactivity affect individuals' understanding of the impact of their behaviors on the environment, encouraging pro-environmental behaviors. Additionally, we draw on the pedagogy literature to explicate that the effects of visualization on learning outcomes and pro-environmental practices can be explained through individuals' psychological responses in their course of interpreting the visualization. Collectively, this study presents our endeavor in understanding the roles of visualization in ecological discourse by integrating the visualization literature and sustainability research. Moreover, by unboxing individuals' psychological processes in interpreting visualization, we offer a fresh perspective to understanding the promises and challenges of using visualization for knowledge acquisition.

Keywords: data visualization, driving simulation, eye-tracking, galvanic skin response, facial expression analysis

Introduction

Debunking sustainability excuses is essential to changing people's mindsets that endanger our collective survival (Kassel et al. 2016). Pro-environmental behaviors depend firmly on individuals' sustainability knowledge about what sustainability entails (Schultze and Orlikowski 2010). Some individuals pursue sustainability as a narrow concept focusing on responsible consumption, while others might see sustainability as an all-encompassing concept, pursuing pro-environmental practices in every possible way. In some cases, individuals might assume sustainability issues to be a collective problem, hence remaining a-motivated to adopt pro-environmental practices. Scientists have repetitively warned that there is a race against time to preserve perhaps what has not been damaged already in the environment and to repair what is left to be restored (Arora and Mishra 2019). Considering the urgency of environmental issues, it is imperative to devise an effective strategy to address these vast differences in sustainability knowledge.

Promoting sustainability knowledge is increasingly drawing the attention of educators and layperson citizens. Learning about sustainability is essential in changing people's mindsets that endanger our collective survival (Kassel et al. 2016). Formal ecological discourse focuses on elucidating how the collective responsibilities in environmental problems. For instance, the workplace environmental training program at the Fujitsu group focuses on providing comprehensive ecological education, such as sustainable development goals, organizational zero-emission strategies, and specialized skill training. By contrast, informal ecological discourse often adapts a personalized discourse strategy. To illustrate, in addition to the workplace environmental training program, the Fujitsu group has also adapted experiential eco-tour to facilitate employees' personal and direct exposure to actual ecological issues.

Information Systems (IS) research has long since pioneered the advancement of ecological discourse with technologies. Early research focuses on identifying technological characteristics to advance sustainable business practices, such as online simulations, energy informatics, and telecommuting (Seidel et al. 2013; Watson et al. 2010). Recent research has begun to examine adopting technologies to promote environmental awareness and support sustainability behaviors, such as household smart metering technology and digital green promotion campaigns (Leung et al. 2019; Wunderlich et al. 2019). Overall, while IS research has significantly enriched our understanding of the impact of technologies on promoting sustainability knowledge and pro-environmental behaviors, rarely has past research devised a coherent explanation to elucidate individuals' psychology in understanding digitalized environmental discourse.

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This study sets to advance the IS literature by investigating the effects of visualization on promoting sustainability knowledge and pro-environmental behaviors. Specifically, drawing on the visualization literature, we explain how the key visualization features, expectancy illustration, and interactivity affect individuals' understanding of the impact of their behaviors on the environment, encouraging pro-environmental behaviors. Additionally, we draw on the pedagogy literature to explicate that the effects of visualization on learning outcomes and pro-environmental practices can be explained through individuals' psychological responses in their course of interpreting the visualization. Collectively, this study presents our endeavor to understand the roles of visualization in ecological discourse by integrating visualization literature and sustainability research. Moreover, by unboxing individuals' psychological processes in interpreting visualization, we offer a fresh perspective to understanding the promises and challenges of using visualization for knowledge acquisition.

Related Literature

Pro-environmental Behavior and Sustainability Knowledge

Pro-environmental behavior refers to actions that not only cause minimal damage to the natural environment but can also benefit it (Arora & Mishra, 2019). Early sustainability research has generally focused on a single type of pro-environmental behavior. For instance, Vining and Ebreo (1992) examined household participation in voluntary curbside recycling programs and found that general environmental understanding was essential for encouraging recycling practices. More recent research has begun to recognize pro-environmental behavior as a heterogeneous, multidimensional construct that includes both private and public sphere behaviors. Private sphere pro-environmental behavior focuses on maintaining green consumption through responsible, selective purchase, usage, and disposal. Often, private pro-environmental behavior can be exercised without directly benefiting others. The prime examples of private sphere pro-environmental behavior are eco-driving behavior and recycling behavior. Eco-driving behavior is a fuel-efficient driving technique that focuses on maintaining consistent driving speed and avoiding unnecessary harsh speed changes (Barkenbus 2010). Recycling behavior is defined as separating waste according to its structure or material types (e.g., paper, plastic, and metal) (Apinhapath 2014). Whereas eco-driving focuses on reducing the negative impact of vehicular operations on the environment, recycling can benefit the environment by preventing emissions of greenhouse gases and water pollutants.

Sustainability knowledge and pro-environmental behaviors are widely recognized for their importance in saving the world from the brink of ecological disasters, such as sea-level increase, global warming, and worldwide biodiversity loss. Sustainability knowledge is defined as an individual's cognitive realm related to the environment, that is, facts, concepts, and relation to environmental problems (Hwang et al. 2020). Scholars have categorically advanced that sustainability knowledge is a precondition for adopting pro-environmental behavior. For instance, Chen et al. (2019) observed that education levels were closely associated with sustainability knowledge, an essential driver for adopting a sustainable lifestyle. Given the apparent societal and economic importance of sustainability, governments, and organizations are devoting increasing resources to sustainability training. However, little attention remains regarding how specific sustainability training for individuals influences environmental proactivity (Vidal-Salazar et al. 2012).

Expectancy Illustration

Expectancy illustration is often employed in visualization to explain or describe processes leading to outcomes. Often, expectancy illustration is facilitated through data storytelling, which helps an audience focus on the essential information in understanding processes. The data storytelling technique provides visualization designers with a set of "golden principles" that can be applied to enhance learning (Knaflic 2015). In particular, experts recommend that knowledge acquisition can be optimized through expectancy illustration when individuals can effectively visualize not only the eventual outcome but also the intermediate outcome.

This study considers two types of expectancy illustration, namely partial causal illustration and complete causal illustration. Partial causal illustration focuses on explaining the eventual outcome of an issue. The Human-Computer Interactions (HCI) literature has extensively discussed the prevalence of visualizations that employ partial causal illustration. For instance, in the context of health discourse, Oh et al. (2018) found that visualization of an obese character allowed individuals to vividly visualize the impact of overeating on future obesity problems. More importantly, partial causal illustration improved individuals' awareness about obese individuals' hardships and elevated their severity perception associated with obesity. Collectively, past evidence suggests that partial causal illustration improves individuals' comprehension of distal consequences of ongoing activities, improving their overall understanding of complex issues.

While partial causal illustration has been broadly employed in promoting environmental awareness, recent public discourse efforts have begun to utilize visualization with complete causal illustration. In particular, visualization designers have advanced the importance of incorporating visualization on distal, eventual outcomes with visualization with concrete illustrations of intermediate consequences. For instance, Swan (2013) found that visualization of personal data, such as sleep quality data and physical activity data, enabled individuals to recall various aspects of their daily life, which were helpful to individuals' understanding of their immediate health status and comprehending the potential long-term well-being.

Despite accumulating evidence of the effectiveness of expectancy illustration, rarely has past research systematically examined the underlying mechanics. To address this gap, this study draws on the expectancy theory of motivation to advance a concrete theoretical explanation. The theory postulates that an individual can be motivated to change the way he or she performs a task when the individual believes the change will lead to performance improvement, which in turn will increase the chances of achieving a rewarding outcome that is important to his or her personal goals and needs (Vroom et al. 2015). Scholars have drawn on the theory to understand how individuals can be motivated to change their behaviors in various contexts, such as working environments, academic settings, and online knowledge-sharing (Liu et al. 2020; Steel and König 2006).

According to Vroom (2015), motivation to maintain behavioral changes is a function of expectancy and instrumentality. Expectancy is about one's assessment of his or her efficacy of achieving immediate performance improvement with additional efforts (Perez et al. 2019). A strong perception of expectancy is indicative of individuals' belief about their capability of executing actions required to attain designated performance improvement (Eden 1988). Evidence suggests that individuals often formulate expectancy by reflecting on past performance, which enables them to identify weaknesses and channel subsequent efforts to address those issues for performance improvement. For example, in a study examining personal fitness informatics, Clinger (2015) found that feedback on users' past exercise intensity and dietary intake could elevate competence feelings by emphasizing their progress in weight management, which powerfully enhanced users' expectancy perception of losing weight.

Instrumentality centers on one's confidence that improved performance would lead to desired outcomes (Parijat and Bagga 2014). Past motivation research has generally suggested that when individuals become cognizant of an important eventual outcome, they would be motivated to sustain the performance improvement necessary for achieving that eventual outcome (Cadsby et al. 2007). Indeed, empirical evidence has revealed the importance of keeping individuals aware of both tangible and intangible outcomes in maintaining performance improvement. In work settings, He et al. (2021) showed that pay-for-performance systems enabled transparency on work quality and employee compensation, which could motivate employees to maintain high productivity. Additionally, in the aforementioned study, Clinger (2015) noted that the effects of personal fitness informatics on fitness maintenance became more sustainable when individuals maintained a vivid awareness of the importance of fitness in preventing future chronic diseases. Consistent with the expectancy theory of motivation, with partial causal illustration, the visualizations focus on depicting how general activities (i.e., emission activities) lead to future environmental consequences. With complete causal illustration, the visualizations begin with illustrating the impact of individuals' actual behaviors on immediate environmental consequences, followed by the future ecological outcome.

Interactivity

Interactivity has rapidly come to the forefront of contemporary visualization designs. Interactivity employed in visualization is primarily concerned with how individuals are allowed to operate or act upon the visual data representations (Sedig and Sumner 2006). More importantly, interactivity has also been advocated for resolving the typical split-attention problem, where multiple visual objects simultaneously compete for one's attention (Rosenholtz et al. 2007). Consequently, individuals would struggle to draw associations between multiple visualizations, and more detrimentally, reducing their ability to comprehend multiple pieces of information and acquire knowledge through information integration (Erhel and Jamet 2006). Yet some evidence suggests that interactivity might cause unnecessary distractions, and hence be detrimental to understanding visualization (Perin et al. 2013).

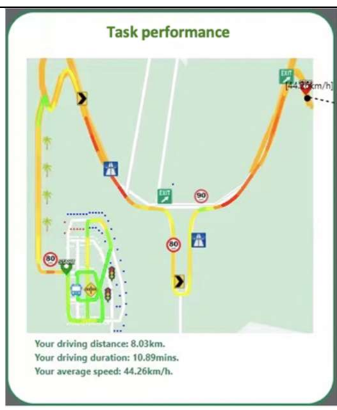
This study draws on the pedagogical literature to devise a fundamental theoretical explanation of interactivity. According to the literature, content segmentation and relational linkage are particularly helpful in drawing learners' attention to the relevant, associated information units (Florax and Ploetzner 2010). Whereas content segmentation reduces learners' cognitive effort in acquiring knowledge, relational linkage facilitates the establishment of connections among a divergent set of information. The segmenting principle explains that segmentation breaks down learning material into multiple segments of information, which helps learners focus on processing a cluster of related information, before moving on to another information cluster (Ibrahim et al. 2012). More importantly, the principle offers that the theoretical rationale for segmenting is to manage cognitive processing by partitioning a large learning task into multiple, sequential learning segments. Furthermore, content segmenting encourages scaffolding structural knowledge acquisition (Jonassen et al. 2013), which helps individuals comprehend complex issues such as correlation and covariance between multiple measures and cause-and-effect relationships. Simply put, content segmentation reduces the cognitive load issue with split attention by limiting individuals' attention to a subset of content, hence improving knowledge acquisition.

Relational linkage is about providing visual referents to aid learners in establishing connections between corresponding information units. It is consistently found to be essential to help individuals construct integrated mental representations among multiple units of information. Past research has examined various forms of relational linkages, such as visual indicators, color coding, and connectivity cues (Craig et al. 2002; Kalyuga et al. 1999), to guide individuals' integration of related information elements. Considering the prevalence of content segmentation and relational linkage, this study examines interactive segment linkage on visualization. Without interactive segment linkage, to interpret multiple visualizations, individuals may comprehend each of the visualizations sequentially or selectively compare related segments of respective visualizations. Whereas the former strategy is likely to make individuals struggle to fully comprehend multiple visualizations due to limited cognitive capacities, the latter strategy would require substantial cognitive efforts in managing multiple attention traversal between visualizations. By contrast, when interactive segment linkage is available, individuals will be visually prompted to focus on the predefined segments, instead of randomly comparing visualizations by mentally constructing the corresponding partitions. Furthermore, interactive segment linkage explicates connections between predefined segments with explicit linkage cues, hence externalizing individuals' cognitive efforts in drawing segment associations.

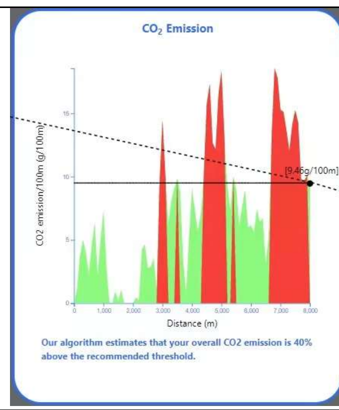
Hypothesis Development

Drawing on the literature on visualization and sustainability, to facilitate a meaningful discourse of the impact of individuals' behaviors on future ecological issues, we constructed three visualizations to depict the environmental impact of behaviors, namely the task performance plot, carbon emission chart, and shrinking sea ice diagram. Following the expectancy literature, to anchor expectancy discourse to individuals' actual behaviors, we required individuals to complete driving tasks using a driving simulator, on which their driving behaviors were captured and subsequently utilized in constructing the task performance plot. This plot was constructed with a color scheme that illustrated individuals' driving speed changes (Figure 1A). The carbon emission chart (Figure 1B) enabled individuals to visualize the estimated amount of carbon emission that individuals had generated based on their driving behavior depicted in the task performance plot. The shrinking sea ice diagram (Figure 1C) helped individuals visualize the association between the future environmental impact (i.e., the extent of sea ice shrinking) and the amount of carbon emission depicted in the carbon emission chart.

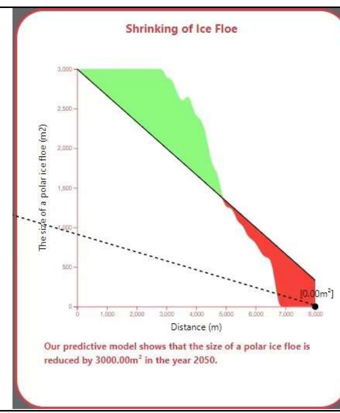
Using the three visualizations, we examine the effects of expectancy illustration on promoting sustainability knowledge and pro-environmental practices. Specifically, we examine two types of expectancy illustration, i.e., partial causal illustration and complete causal illustration. Additionally, this study examines two modes of interactivity, i.e., without interactive segment linkage versus with interactive segment linkage. Finally, to understand individuals' psychological processes in interpreting visualizations, we examine how cognitive operations and emotional responses would mediate the effects of expectancy illustration and interactivity on ecological understanding and behaviors.



1A: Task performance plot



1B: Carbon emission chart



1C: Shrinking sea ice diagram

Figure 1. Visualizations

The Main Effect of Expectancy Illustration

Expectancy illustration is known to improve understanding and promote behavioral changes (Reinharth and Wahba 1975; Steel and König 2006). Specifically, when individuals are aware of both the expectancy and instrumentality of changing their present behaviors, they can fully recognize the immediate consequences, and more importantly, the effects of the immediate consequences on future outcomes. On the contrary, when individuals are only aware of the instrumentality of immediate consequences, they might not be able to concretely associate their present behaviors with future outcomes and hence struggle to understand the complete cause-and-effect. In sustainability visualizations, individuals may be presented with partial causal illustration or complete causal illustration. With partial causal illustration, individuals are made known to the impact of the immediate emission outcomes on future environmental damage. As a result, individuals' direct responsibility for causing environmental damage is likely to become less apparent. By contrast, complete causal illustration concretely presents the associations between individuals' behaviors, the immediate emission outcomes, and the future environmental impact that allows individuals to fully comprehend the ecological consequences of their actual behaviors. Thus, we posit the following:

H1: Compared with partial causal illustration, complete causal illustration will improve sustainability knowledge and pro-environmental practices.

The Joint Effect of Expectancy Illustration and Interactivity

Interactivity in visualization is largely concerned with the manner in which individuals are allowed to operate or act upon the visual data representations (Sedig and Sumner 2006). More importantly, interactivity has also been advocated for resolving the typical split-attention problem, where multiple visual objects simultaneously compete for one's attention (Rosenholtz et al. 2007). Consequently, individuals would struggle to draw associations between multiple visualizations, and more detrimentally, reducing their ability to comprehend multiple information and acquire knowledge through information integration (Erhel and Jamet 2006). Yet some evidence suggests that interactivity might cause unnecessary distractions, and hence be detrimental to understanding visualization (Perin et al. 2013).

Past expectancy research suggests that the effect of expectancy illustration on sustainability knowledge and sustainable practices can be moderated by interactivity. With the absence of interactive segment linkage, individuals largely rely on their mental efforts to integrate information from multiple visualizations. As such, when individuals are presented with partial causal illustration, they are likely to traverse their attention between two visualizations to comprehend the impact of the immediate emission outcomes on future environmental damage. Complete causal illustration is expected to increase the cognitive load in comprehending individuals' responsibilities in damaging the future environment. While understanding of partial causal illustration involves information integration between two visualizations, understanding of complete causal illustration involves information integration between three visualizations. Therefore, without interactive segment linkage, the additional cognitive load required by integrating three information sources will significantly inhibit learning and hence exacerbate sustainability knowledge and sustainable practices.

By contrast, with the presence of interactive segment linkage, individuals are augmented with content segmentation and relational linkage in interpreting visualizations. Accordingly, complete causal illustration is not likely to contribute to increased cognitive load. Rather, with interactive segment linkage, individuals would likely be able to fully comprehend multiple visualizations, hence acquiring a complete understanding of both the primary and secondary environmental impacts of their behaviors. We thus hypothesize the following:

H2A: With the absence of interactive segment linkage, compared with partial causal illustration, complete causal illustration will impede sustainability knowledge and pro-environmental practices.

H2B: With the presence of interactive segment linkage, compared with partial causal illustration, complete causal illustration will improve sustainability knowledge and pro-environmental practices.

The Mediating Roles of Cognitive Operations and Emotional Responses

Past psychology research and the pedagogy literature have advanced an understanding of the effects of variations in visual presentations on reading and understanding. Yet past research has rarely uncovered the underlying cognitive operations that individuals undergo when they are performing information integration. A possible reason is that extant work might predominately rely on survey questionnaires to capture respondents' psychological responses. Consequently, measures of cognitive operations are limited to respondents' recall that can be highly inaccurate, if not entirely unable, to reveal the fine-grained changes in cognitions during information integration. While some research has employed the verbal protocol (i.e., the think-aloud method) in attempting to reveal individuals' mental processes, study respondents would need to be extensively trained to perform think-aloud tasks that are not entirely natural activities. More importantly, since cognitive operations can occur subliminally, even experienced respondents might fail to fully articulate their mental processes.

Contemporary IS research has begun to overcome these limitations by employing advanced physiological measures. For instance, in a study examining cognitive processes using eye tracking, Bera et al. (2019) revealed that task performance could be explained by various mental processes, reflected in specific eye-tracking behaviors, where different information presentation techniques invoked different cognitive processes. More importantly, the authors illustrated that visual attention could be utilized to accurately capture individuals' cognitive integration in reading on-screen information. Correspondingly, this study focuses on visual attention and visual association to examine individuals' cognitive operations when they are viewing visualization. Whereas visual attention is about an individual's eye fixations on an on-screen location, visual association, also termed saccades, is about an individual's continuous eye movement between fixations. Visual attention has been broadly employed to measure cognitive processing (Just and Carpenter 1976), such as fixation duration and fixation count.

As individuals engage in learning activities, they often experience an array of affective states that impact their understanding (D'Mello, 2013). It is important to understand individuals' emotions in learning because differences in learners' affects are associated with differences in both immediate learning outcomes (i.e., examination performance) and extended learning outcomes (i.e., application of knowledge in real-life settings). In particular, negative emotions, which are often viewed as emotional responses to unexpected obstacles impeding goal achievement, are shown to be especially detrimental to the learning (Bessiere et al. 2006). Past IS research has concretely illustrated the associations between poorly designed information presentations and negative emotions, such as annoyance, irritation, and frustration (Beaudry and Pinsonneault 2010; Califf et al. 2020).

This study considers two key aspects of emotional responses, namely emotional valence and emotional arousal. Emotional valence refers to the overall degree of unpleasantness or pleasantness of a learning experience facilitated by visualization. Poorly structured and incomprehensible visualization requires individuals to exert substantial efforts to interpret the content, hence challenging their ability to integrate the information to acquire meaningful understanding. Consequently, when substantial efforts are required to understand visualization, individuals are likely to experience negative emotions. By contrast, well-designed visualization reduces individuals' interpretation efforts, which in turn allows them to focus on information integration that is essential for acquiring knowledge.

Emotional arousal is about the intensity of an activated emotional state (Kim et al. 2021). The arousal-based competition theory explains that visualization draws individuals' attention by inciting arousal. Visualization with salient visual features (e.g., luminance, motion, and interactivity) would incite arousal, while visualization with indistinct features is unlikely to be emotionally arousing. More importantly, arousal dominates individuals' attention, hence improving learning about the features. In contrast, with the absence of salient visual features in visualization, individuals' attention will not be maintained, hence impairing their comprehension.

Recent development in psychological construal argues that individuals' psychological responses mediate the effect of expectancy illustration and interactivity on their knowledge acquisition and subsequent behaviors. In other words, psychological responses can be induced through expectancy illustration and interactivity, by which knowledge can be acquired and behaviors can be altered after exposing individuals to information presentation. It is important to note that these conceptual linkages (i.e., information presentation → psychological responses; psychological responses → behavioral changes) have been robustly demonstrated in other contexts. For instance, Choi et al. (2019) showed that individuals' cognitive and emotional responses could be simultaneously determined by various fairness information presentations after an online security breach. It is also consistent with previous behavioral studies that considered individuals' psychological responses as the determinants of behavioral changes. For instance, Liang et al. (2019)proposed that individuals' cognitive appraisal of information technology risk and emotions aroused by security breaches influenced their motivations to take corrective actions.

Extending the relationship between information presentation and psychological responses, we argue that cognitive operations and emotional responses mediate the relationship between visualization and sustainability knowledge as well as sustainable practices. While some researchers have observed that visualization can facilitate knowledge acquisition, leading to improved learning outcomes and behavioral changes, others have demonstrated that when visualization comprehensibility is an issue, learning might occur with frustration and annoyance. Therefore, we suggest that the effects of expectancy illustration and interactivity on sustainability knowledge and sustainable practices are mediated by cognitive operations and emotional responses.

H3A: The effects of expectancy illustration and interactivity on sustainability knowledge and pro-environmental practices are mediated by cognitive operations.

H3B: The effects of expectancy illustration and interactivity on sustainability knowledge and pro-environmental practices are mediated by emotional responses.

Research Method

A laboratory experiment with 2 (expectancy illustration: partial causal illustration versus complete causal illustration) by 2 (interactivity: without interactive segment linkage versus with interactive segment linkage) between-subjects factorial design was conducted to test the proposed hypotheses. Expectancy illustration in the experiment was manipulated by presenting either two visualizations (i.e., the carbon emission chart and the shrinking sea ice diagram) or three visualizations (the task performance plot, the carbon emission chart, and the shrinking sea ice diagram). The carbon emission chart and shrinking sea ice diagram enable subjects to develop a sense of instrumentality on how the primary environmental consequences can lead to secondary ecological outcomes. The task performance plot and carbon emission chart enable subjects to formulate an expectancy about their efficacy of influencing the primary environmental consequences through present behaviors.

Interactivity was manipulated by presenting the visualizations with or without interactive segment linkage. With interactive segment linkage, the visualizations were constructed with a dynamic referencing mechanism, in which subjects were provided with visual linkages (i.e., a dynamically constructed line connecting the corresponding segments of two visualizations) that guide their attention to a specific segment of a visualization (e.g., the first unit of distance on the task performance plot) and its associated segment on another visualization (i.e., the corresponding first unit of emission on the carbon emission chart).

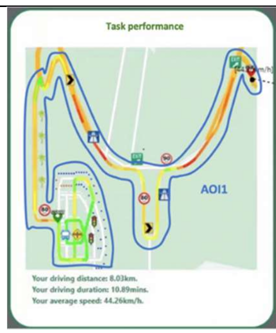
The Mediating Roles of Cognitive Operations and Emotional Responses

Past psychology research and the pedagogy literature have advanced an understanding of the effects of variations in visual presentations on reading and understanding. Yet past research has rarely uncovered the underlying cognitive operations that individuals undergo when they are performing information integration. A possible reason is that extant work might predominately rely on survey questionnaires to capture respondents' psychological responses. Consequently, measures of cognitive operations are limited to respondents' recall that can be highly inaccurate, if not entirely unable, to reveal the fine-grained changes in cognitions during information integration. While some research has employed the verbal protocol (i.e., the think-aloud method) in attempting to reveal individuals' mental processes, study respondents would need to be extensively trained to perform think-aloud tasks that are not entirely natural activities. More importantly, since cognitive operations can occur subliminally, even experienced respondents might fail to fully articulate their mental processes.

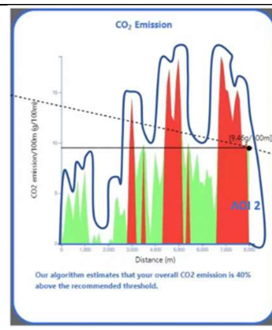
Sample and Experimental Procedures

One hundred and eighty-three subjects, who were adults with valid driving qualifications and driving experiences, participated in the experiment. Subjects were randomly assigned to one of the four experimental conditions. Upon arrival at the laboratory, subjects were seated at a desk in a temperature and humidity-controlled room. Afterwards, subjects were put through a calibration with the eye-tracking equipment and hooked up with the galvanic skin responses (GSR) sensors. They were instructed to complete a filler task (i.e., ten simple arithmetic problems) to get them accommodated with the sensor (Croyle and Cooper 1983). They were asked to remain seated and relax for three minutes upon completing the filler task.

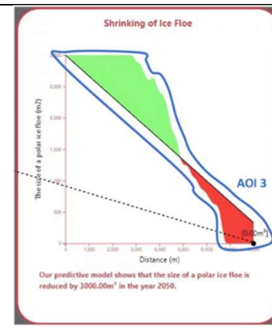
Figure 2. Driving simulation environment



3A: Task performance plot



3B: Carbon emission chart



3C: Shrinking sea ice diagram

Figure 3. AOIs

Subjects were instructed to complete three rounds of the driving simulation (i.e., a familiarization drive, the first scenario drive, and the second scenario drive). Figure 2 shows the screen demonstrating the driving simulation environment, in which a subject was driving approaching a signalized intersection. The key objective of the familiarization drive was to get subjects accustomed to the driving simulation environment. Subjects were encouraged to spend time getting used to the driving simulator. After completing the 1st scenario drive, subjects were presented with visualizations on the environmental impact of their driving behaviors in the 1st scenario drive. To help subjects understand the visualizations, they were first presented with empty visualizations. Subjects were asked to carefully read the detailed descriptions of each visualization (e.g., descriptions of the color intensity scheme in the task performance plot, explanations of the computation of subjects' carbon emission, and explanations of the predictive model utilized for estimating sea-ice shrinking). Upon completing the descriptions, subjects would initiate the visualizations that were presented based on their randomly assigned experimental conditions. Subjects then completed the final round of stimulation driving. Afterward, subjects were asked to attempt a quiz and a carbon offsetting task. The quiz consisted of six questions evaluating subjects' understanding of visualizations. In the carbon offsetting task, subjects were informed that they might utilize a hand crank charger to generate electricity to offset the carbon footprint associated with the conduct of the experiment. To avoid sequence effects, the quiz and carbon offsetting task were presented in random order.

We utilized eye-tracking to facilitate objective measures of subjects' cognitive operations while viewing the visualizations. Following past eye-tracking research, to systematically quantify subjects' cognitive operations, we defined areas of interest to categorize eye fixation and dwell time percentage in specific regions (Blascheck et al. 2017). Accordingly, to capture subjects' visual attention while viewing the visualizations, we have created 1 distinct area of interest (AOI) on the task performance plot, 1 AOI on the carbon emission chart, and 1 AOI on the shrinking sea ice diagram (Figure 3).

Data Analysis

Among the 183 subjects, 94 were female. The age of the subjects ranged from 25 to 31, with the average driving experience and average driving frequency being 5.12 years of license age and 15.01 times per month, respectively. No significant differences were found among subjects randomly assigned to each of the four experimental conditions concerning age, gender, driving experience, and driving frequency, indicating that subjects' demographics were relatively homogeneous across different conditions.

Operationalizations

Following the eye-tracking literature (Bera et al. 2019), we operationalize visual attention allocation to each AOI regarding fixation count and dwell time percentage. Fixations are about the period during which a subject's eyes focus on an AOI (Fischer and Ramsperger 1984). Dwell time percentage is about the proportion of time a subject fixated on an AOI within a period. Emotional response was operationalized in two components: emotional arousal and emotional valence (Russell 1989). Galvanic skin response (GSR) is an objective, valid, and reliable measure of physiological arousal. Therefore, to operationalize physiological arousal, we collected subjects' average GSR scores during the period when they were viewing the visualizations.

This study employed automatic facial expression analysis (FEA) using computer vision to operationalize emotional valence. Following the general FEA practices, our analysis consists of three steps, namely (i) face detection, (ii) facial feature detection, and (iii) facial expression and emotion classification. Face detection is the process in which an algorithm is applied to detect a subject's face in a video frame. Facial feature detection is performed by detecting facial landmarks such as eyes, brows, mouth, and other facial features. Facial expression and emotion classification focus on matching the detected facial features with pre-established facial appearance databases. Using the FEA results, we computed the proportion of time subjects experienced positive valanced emotions and negative valanced emotions while viewing the visualizations.

To assess subjects' sustainability knowledge after viewing the visualizations, we constructed a quiz with six questions covering the six fundamental categories of knowledge, namely remembering, understanding, applying, analyzing, evaluating, and creating. A higher quiz score indicates better sustainability knowledge. These questions are related to causes of carbon pollution (e.g., poor efficiency in fossil-fired power generation, inefficient vehicle operating practices, and poor manure management) and the environmental impacts of carbon pollution (e.g., increase in average annual temperatures, decrease in snow, sea ice, and glacier coverage, rise in sea levels and increase in coastal flooding, and increase in overall precipitation levels)

Pro-environmental practices were considered in two aspects, namely driving efficiency scores and carbon offset efforts. Driving efficiency scores were computed based on the subjects' driving patterns in the simulation. Following Chen et al. (2019), we adapted the Symbolic Aggregate Approximation (SAX) method to translate a subject's simulation driving data (i.e., the recorded speed at every 0.1 seconds) into a single score. A higher score indicates more efficient driving behaviors. Carbon offset efforts were operationalized based on the number of rotations and the total time duration that subjects had completed on the hand crank charger.

Preliminary Analysis of the Eye-tracking Data

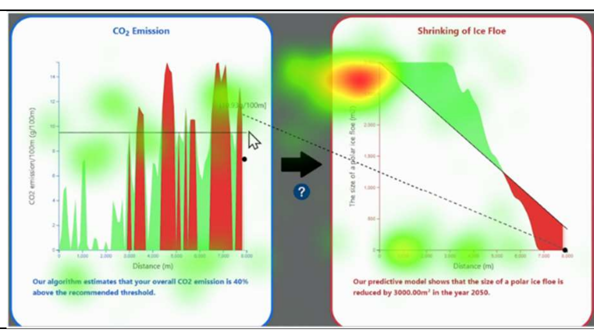


Figure 4. Heat Map on Visualizations with Partial Causal Illustration

Following the eye-tracking literature, we generated heat maps to visualize the overall difference in terms of visual attention between experimental conditions (Schultze and Orlikowski 2010). Heat map is helpful in showing the most and least attention capturing regions on our visualizations. Various colors on a heat map indicate different attentional intensities: warmer colors (e.g., red) indicate more attention, colder colors (e.g., green) indicate less attention, and no color indicates no attention. Visual inspection of the heat maps based on fixations shows the overall impression that subjects assigned to the complete causal illustration condition (Figure 5) paid more attention to the visualizations compared to subjects assigned to the partial causal illustration condition (Figure 4). In particular, compared to subjects assigned to the partial causal illustration condition, subjects assigned to the complete causal illustration condition paid additional attention to the task performance plot. Moreover, subjects in the complete causal illustration condition allocated substantially more attention to the carbon emission chart and the shrinking sea ice diagram.

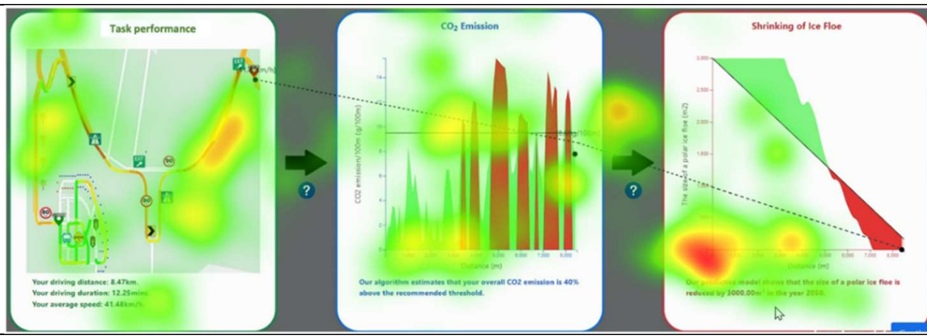


Figure 5. Heat Map on Visualizations with Complete Causal Illustration

In the manipulation checks, subjects provided the answers corresponding to their respective experimental conditions, suggesting that the manipulation for change illustration and narrative sequence was successful. The manipulation check for presentation concurrency was performed by asking subjects three true/false questions on whether the visualization was presented staggered. All subjects answered the question corresponding to their experiment conditions, hence suggesting that the manipulation for presentation concurrency was successful.

Tests of Direct Effect Hypotheses

ANOVA with sustainability knowledge as the dependent variable reveals the significant effects of expectancy illustration and interactivity. Therefore, compared with partial causal illustration, complete causal illustration improves sustainability knowledge. Since the interaction effect on sustainability knowledge is significant ($F(1,179) = 18.66$, $p < 0.01$), we further conducted the simple main effect analysis. Simple main effect analysis reveals that (1) complete causal illustration is associated with significantly higher level of sustainability knowledge than partial causal illustration under the presence of interactive segment linkage ($F(1,88) = 53.61$, $p < 0.01$), and (2) complete causal illustration and partial causal illustration are not different from each other in affecting sustainability knowledge with the absence of interactive segment linkage ($F(1,91) = 0.07$, $p = 0.79$) (see Table 1, Figure 6).

	wISL	ISL	Mean
PCI	5.06	6.07	5.57
CCI	4.92	9.87	7.39
Mean	4.99	7.97	

Table 1. Mean Values of Sustainability Knowledge

Note. wISL, without interactive segment linkage; ISL, interactive segment linkage; PCI, partial causal illustration; CCI, complete causal illustration.

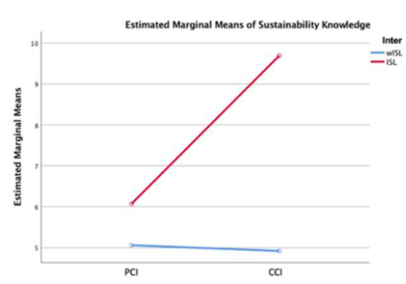


Figure 6. Mean Plot of Sustainability Knowledge

ANOVA with driving efficiency scores as the dependent variable reveals the significant effects of expectancy illustration and interactivity. Furthermore, ANOVA with the number of rotations as the dependent variable reveals the significant effects of expectancy illustration and interactivity. Lastly, ANOVA with time spent in electricity generation as the dependent variable reveals the significant effects of expectancy illustration and interactivity. Collectively, compared with partial causal illustration, complete causal illustration will improve sustainability knowledge and pro-environmental practices. Therefore, H1 is supported.

Since the interaction effect on pro-environmental practices was significant, we further conducted the simple main effect analysis. Results suggest that the effect of complete causal illustration is moderated by interactive segment linkage. Simple main effect analysis reveals that (1) complete causal illustration is associated with significantly higher driving efficiency scores ($F(1,88) = 18.48$, $p < 0.01$) (see Table 2, Figure 7), more rotations in electricity generation ($F(1,88) = 7.82$, $p < 0.05$) (see Table 3, Figure 8), and time spent in electricity generation ($F(1,88) = 5.60$, $p < 0.05$) (see Table 4, Figure 9) than partial causal illustration under the presence of interactive segment linkage, and (2) complete causal illustration and partial causal illustration are not different from each other in affecting pro-environmental practices with the absence of interactive segment linkage. Collectively, H2A is not supported but H2B is supported.

	wISL	ISL	Mean
PCI	0.55	0.63	0.59
CCI	0.51	0.74	0.62
Mean	0.53	0.68	

Table 2. Mean Values of Driving Efficiency Scores

	wISL	ISL	Mean
PCI	158.16	192.61	175.38
CCI	158.48	220.55	189.51
Mean	158.32	206.58	

Table 3. Mean Values of Number of Rotations

	wISL	ISL	Mean
PCI	137.18	148.33	142.76
CCI	136.56	173.74	155.15
Mean	136.87	161.04	

Table 4. Mean Values of Time Spent

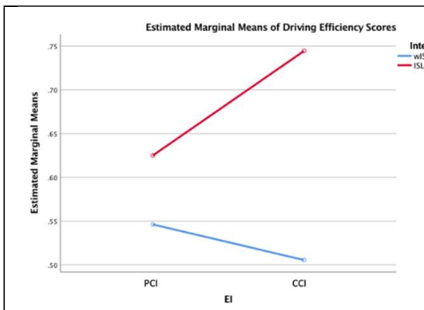


Figure 7. Mean Plot of Driving Efficiency Scores

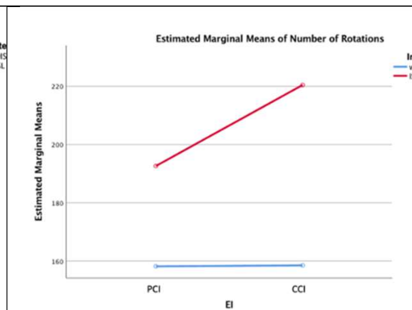


Figure 8. Mean Plot of Number of Rotations

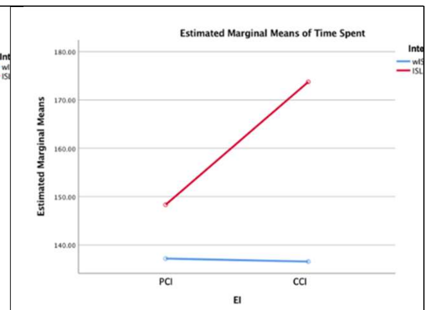


Figure 9. Mean Plot of Time Spent

Tests of Mediated Effect Hypotheses

We posit that the effects of expectancy illustration and interactivity on sustainability knowledge and pro-environmental practices are mediated by cognitive operations and emotional responses. To test the hypothesized mediation effects, we utilized the procedure proposed by Preacher and Hayes (2004). Results reported suggest that cognitive operations significantly mediate the direct effects. Therefore, H3a is supported but H3b is not supported.

Discussion of Results

Our results supported most of our hypotheses. First, we hypothesized that complete causal illustration led to better sustainability knowledge and pro-environmental practices than partial causal illustration. We found that subjects in the complete causal illustration condition achieved better sustainability quiz results, higher driving efficiency scores, more rotations in electricity generation, and longer duration in electricity generation. We also argued that the effects of complete causal illustration interacted with interactive segment linkage in influencing sustainability knowledge and pro-environmental behaviors. Our results showed that with interactive segment linkage, complete causal illustration indeed improved green learning and promoted pro-environmental practices.

Additionally, our results showed that cognitive operations and emotional responses mediated the effects of visualizations on sustainability knowledge and pro-environmental behaviors. Consistent with our prediction, complete causal illustration complemented by interactive segment linkage powerfully influenced cognitive operations, which in turn affected sustainability knowledge and pro-environmental practices. Additionally, our results showed that the effects of expectancy illustration and interactivity on pro-environmental practices were only mediated by emotional arousal.

We posited that complete causal illustration would lead to worse sustainability knowledge and pro-environmental behaviors when interactive segment linkage was absent. Contrary to my expectation, the results showed that the joint effects on the outcomes were not significant. A plausible explanation is that compared with partial causal illustration, complete causal illustration presented greater visual complexity and demanded greater information integration efforts, which could be detrimental to acquiring sustainability knowledge and promoting pro-environmental behaviors. In the meanwhile, without interactive segment linkage, individuals could find it similarly demanding to fully comprehend and integrate the information, regardless of the number of presented visualizations. Instead of engaging in deliberate information processing, individuals were likely to utilize peripheral processing to bypass interpreting the details. Consequently, without interactive segment linkage, differences in learning outcome and behavior promotion became indifferentiable.

Also, unexpectedly, our results showed that the mediation effects of expectancy illustration and interactivity on sustainability knowledge through emotional responses were not significant. We believe that the absence of such mediation effect could be largely explained by the nature of the quiz. Although our quiz was designed to achieve a comprehensive assessment of the knowledge, the assessment was unavoidably rooted in the visualization content. Such issues were not atypical, especially in traditional written examinations that might be most adequate to reflect students' cognitive abilities in understanding, remembering, and reproducing the learned content in examinations. Since individuals' learning experience predominately was explained through cognitive operations, emotional responses were not in play.

Limitations and Future Directions

Our findings need to be interpreted with some limitations in mind. This study examines individuals' sustainability knowledge and pro-environmental practices after viewing visualizations on the environmental impact of their driving behaviors. Cautions must be exercised when generalizing our findings to other visualization context. For instance, our findings might not be completely applicable to designing visualization of household power consumption since momentary, rapid changes in power consumption might not be entirely typical, hence diminishing the explanatory and exploratory capacity facilitated by visualization. We encourage future research to replicate our study in other relevant contexts.

Additionally, this study utilizes a quiz to assess subjects' learning outcome. While our quiz is carefully designed, individual performance in the quiz might be influenced by idiosyncratic differences, such as examination techniques, data literacy, and general intelligence. To illustrate, individuals well-versed in examination techniques might be capable of deducing the correct answers, despite mediocre learning experience. We recommend that future studies consider an even broader populations to verify our findings. Additionally, we focused on utilizing physiological measurement to capture individuals' psychological responses. Future studies can consider triangulating our findings with self-reported measurements.

Implications

This paper makes several important contributions to the literature. First, we contribute to the IS literature by unraveling the effects of visualizations on behaviors. Past visualization research has extensively demonstrated the advantages of visualizations for understanding complex problems. While people might thoroughly understand future environmental issues, they may fail to maintain sustainable behaviors.

Emerging research suggests that green practices can be best encouraged by activating individuals' moral norms toward acting pro-environmentally (Filieri et al. 2021). Such finding has enthused scholars to examine the design and evaluation of visualizations for enhancing individuals' understanding of the environmental impact of their behaviors (Schneider et al. 2023). This study thus makes an important contribution to the IS literature by demonstrating how expectancy illustration and interactivity can be utilized to promote sustainability knowledge and pro-environmental behaviors. Broadly speaking, since visualizations enable individuals to witness the effects of their own behaviors on future, distal consequences, IS research can consider utilizing visualized narratives to further advance digital behavioral interventions.

We also advance the sustainability literature by illustrating the mediating roles of cognitive operations and emotional responses. Although psychological responses have been broadly employed in past sustainability research, substantial debate exists about how best to utilize individuals' psychological responses to understand sustainability knowledge acquisition and promotion of pro-environmental behaviors. One stream of sustainability research shows that individuals' cognitions are important determinant of environmental awareness, while another stream demonstrates that emotional feelings associated with the environment can simultaneously determine pro-environmental behaviors (e.g., Zavareh et al. 2020). This study shed new light on the sustainability literature by explicitly differentiating cognitive operations and emotional responses and demonstrated that these two aspects of psychological responses could influence sustainability knowledge acquisition and pro-environmental behaviors.

We contribute to practice in several important aspects. Our study concretely demonstrates that visualization design requires careful consideration. While some designers might adopt a buffet approach by incorporating as many visual components and interactivity features as possible, we caution that mindful consideration is necessary for employing expectancy illustration and interactivity in visualizations. Specifically, we found that visualizations with complete causal illustration could inhibit sustainability knowledge and pro-environmental practices due to reduced cognitive operations and elevated negative emotional responses. More importantly, the problems associated with complete causal illustration can be overcome using interactive segment linkage. Hence, we recommend that visualization designers might consider supplementing expectancy illustration with exploratory, interactivity features.

Additionally, we also reveal the importance of visualization comprehensibility on cognitive operations and emotional responses. When individuals are confronted with an elevated cognitive load in comprehending complex visualizations, they can struggle to perform effective information integration, which arouses unpleasant emotions and inhibit learning. By contrast, when the cognitive load in comprehending complex visualizations is externalized to interactivity features, effective information integration can be performed, which is vital to ensuring pleasant emotions in learning. Therefore, we recommend that learning content designers should optimize their visual designs by considering cognitive load issues. In designing instrumentality and expectancy content, designers need to prudently consider feasible strategies to facilitate effect content segmentation and relational linkage.

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