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Neuro-Cognitive Differences in Decision-Making about Green and Grey Infrastructure

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NEURO-COGNITIVE DIFFERENCES IN DECISION-MAKING ABOUT GREEN AND GREY INFRASTRUCTURE

ABSTRACT

Decisions about storm water infrastructure are increasingly uncertain due to climate change. More frequent and extreme rainfall events exacerbate the risk of infrastructure failure and water quality deterioration. Green infrastructure can be cost-effective in storm water management and more adaptive to a changing climate. However, traditional grey infrastructure has been dominant over decades and green infrastructure encounters numerous cognitive obstacles in its implementation. Higher perceived uncertainty and a lack of adequate methods to monetize the benefits of green infrastructure can lead to undervaluing its performance in the decision-making process. The purpose of the research presented in this paper was to explore the underlying mechanism involved when making judgements and decisions about green and grey infrastructure. A neuroimaging technique, called functional near infrared spectroscopy (fNIRS) was used to measure the cortical activation of civil and environmental engineering graduate students when making judgements about green and grey infrastructure in storm water infrastructure design scenarios. The results show that engineering students perceive green infrastructure with higher uncertainty and have higher activation in their brain regions associated with cognitive control and risk aversion. These engineering students are willing to pay more for green infrastructure and were observed to have higher cortical activation in their brain regions associated with value computation. This study offers brain-behavior relationships that describe how decision-makers judge and ultimately make a choice between green or grey infrastructure solutions. Future study can test interventions that affect behavior and cognition to change perceptions of uncertainty and further increase willingness to pay for more green infrastructure.

KEYWORDS

Decision-making, green infrastructure, sustainability, neuroscience, functional near-infrared spectroscopy.

INTRODUCTION AND BACKGROUND

Design and decision-making processes for storm water infrastructure face increasing uncertainty due to climate change (O'Donnell et al. 2017). Traditional storm water infrastructure, such as drainpipes, pumps, tunnels, and roadside ditches, are typically designed using data from historical precipitation (Adams and Howard 1986). An assumption during design is extreme precipitations are stationary (Rosenberg et al. 2010). A changing climate is leading to more extreme weather events and resulting in a substantial underestimation of extreme precipitation in the design process (Cheng and AghaKouchak 2014). Increasingly frequent and extreme rainfall events exacerbate the risk of infrastructure failure (Neumann et al. 2015), flooding (Wilby and Keenan 2012; Wheater and Evans 2009), combined sewer overflow (CSOs) (Patz et al. 2008), and water quality deterioration (Hunter 2003). Upgrading current storm water systems is necessary to maintain community well-being (Arnbjerg-Nielsen et al. 2013; Kessler Rebecca 2011; Olsson et al. 2013).

For the past century, traditional concrete and grey infrastructure systems have been the dominant storm water management practice, even though such reliance has led to various unintentional negative impacts in water quality and hydrological cycles (Brears 2018). Additionally, the magnified urban heat island effect, flooding, droughts, and also higher temperature caused by climate change increase the vulnerability of grey infrastructure to a shorter asset life and higher maintenance cost due to the damages such as cracking or erosion (Brears 2018; Jiménez Cisneros et al. 2014). Improving grey infrastructure to achieve a satisfactory performance in a changing climate is costly and disruptive (Olsson et al. 2013; Kessler Rebecca 2011), and the pattern of change in the climate might outpace this improvement (Patz et al. 2008). Dependence on traditional grey infrastructure to manage storm water is neither sustainable nor adaptive to climate change (Brears 2018).

A sustainable and resilient alternative to grey infrastructure is green infrastructure that mimics nature and restores natural water cycles to achieve the function of storm water management (Foster et al. 2011). Green infrastructure is defined as “an interconnected network of green spaces that conserve ecosystem values and functions and provide associated benefits to human populations” (Benedict and MacMahon 2002). Green infrastructure, such as, green roofs, rain gardens, permeable pavements, bio-retention, bio-swales, and rain harvesting, can help to manage storm water (Wise 2008). Green infrastructure is cost-effective to reduce storm water runoff (U.S. Environmental Protection Agency 2013) and also deferring or replacing grey infrastructure, reducing demand and cost for energy, increasing property values, enhancing water quality, reducing the urban heat island effect, increasing quality of life and flood mitigation (Brears 2018; Ghofrani et al. 2017; Jaffe 2010).

Barriers to Green Infrastructure

While there are significant sustainable benefits of green infrastructure, implementation is relatively slow and infrequent (Matthews et al. 2015). Green infrastructure encounters numerous cognitive barriers in design and decision-making processes (Byrne and Yang 2009). Green infrastructure is perceived with higher uncertainty in its cost and performance, since experience is often inadequate and there is a lack of available data to support decision-making processes (Thorne et al. 2015). Storm water infrastructure design practitioners, for instance, report discomfort with the ambiguity about the concept of green infrastructure and an aversion to risk during implementation due to uncertain about the approach and expected outcomes (Wright 2011).

The lack of confidence concerning the public acceptance (Carlet 2015; Thorne et al. 2015), and long-term maintenance of green infrastructure (Ghofrani et al. 2017; Montalto et al. 2011; O’Donnell et al. 2017) further elevates the perceived uncertainty about green infrastructure. Stakeholders averse to higher uncertainty choose to keep with the status quo of grey infrastructure that has been dominant for decades. Another obstacle is quantifying the economic benefits of green infrastructure (Matthews et al. 2015). Measuring the reduction in storm water runoff might be straightforward, but estimating the reduced urban heat island effects, enhanced community livability (e.g. aesthetics, recreation, and health), habitat improvement, and public education are not as easy (Brears 2018; CNT 2011).

The appropriate discount rate for the long term benefits of green infrastructure that are often delayed in time is complex and controversial (Norgoard and Howarth 1991). Decision-makers might discount future value too much or not have long enough of a time horizon in their trade-offs between the upfront cost and future benefits (Brears 2018), especially when green infrastructure can have a higher initial cost. Green roofs, for instance, usually require higher initial cost compared to conventional roofs (Castleton et al. 2010).

The lack of physical space, especially in urban high-density areas, creates conflicts during decision making processes for green infrastructure (Byrne and Yang 2009; Maes et al. 2015). Construction of green infrastructure can require the removal of existing facilities or occupying private land or public space. For example, in an interview about adding bio-swales along roadways in Portland, Oregon, stakeholders expressed their aversion to loss of driving lanes and public parking (Church 2015). Stakeholders were losing a benefit they already had in order to gain new benefits that they might not be totally aware of or have enough knowledge about.

Portland is not the only example of loss aversion in response to green infrastructure. The Cheonggyecheon Linear Park, in the center of Seoul, South Korea, added green space and day-lighted an urban waterway, but it required removing an elevated freeway. Traffic actually reduced without the freeway, so did the ambient air temperature, and property values increased. Yet, the design was initially met with strong protest from the public who did not want to lose the existing infrastructure in order to make room for the new green infrastructure (Lee and Anderson 2013).

Numerous rational models for decision making about infrastructure and under uncertainty exist, but more recent advances in behavioral science demonstrate that decision-makers deviate from these normative models in numerous contexts (Tversky and Kahneman 1992). Cognitive limitations in knowledge and calculation capacities (Simon 1982) influence judgements during the design and decision making process for green infrastructure (Montalto et al. 2011; Kahneman et al. 1991; Kahneman and Tversky 1979). To better understand these cognitive limitations that contribute to less adoption of green infrastructure (e.g. high uncertainty, loss aversion, temporal discounting), the research presented in this paper describes the neuro-cognitive differences of decisions for storm water infrastructure systems. Understanding the underlying cognitive mechanisms that contribute to decision outcomes for green infrastructure, future research can begin to build better descriptive models to explain the cognition limits, and develop corrective actions that encourage greater adoption.

Measure the Cognition of Decision-making for Green Infrastructure

There are three common neuroimaging techniques used to measure patterns of cortical activation in brain: functional near-infrared spectroscopy (fNIRS), electroencephalography (EEG), and functional magnetic resonance imaging (fMRI). fNIRS is used in this study because of its relatively good spatial and temporal resolution (Seo et al. 2010). fNIRS measures patterns of cognitive activation through

Blood Oxygenation Level Dependent (BOLD) response illustrated in Figure 1. It is also portable and worn as a cap making it wearable in both lab and real-world environments (Grohs et al. 2017; Shealy and Hu 2017).

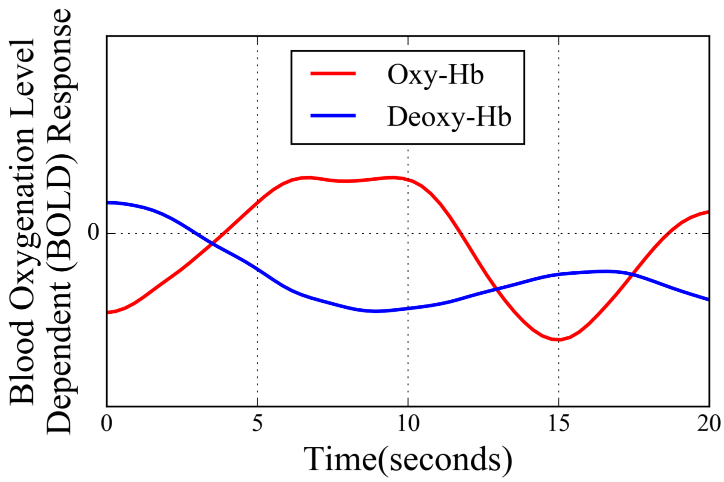

Figure 1: Blood Oxygenation Level Dependent (BOLD) Response

A fNIRS equipment, illustrated in Figure 2, consists sensors (including sources and receivers of light), a wearable cap that holds the sensors, and the data collection hardware connected to sensors that records changes in oxygenated blood in the brain. The sources of light emit near infrared light with two or three specific wavelengths (700-900 nm) into the human cortex. The light scatters, and some is absorbed, by oxygenated hemoglobin (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb) in the blood. The light that is not absorbed is reflected back to the receiver. The oxy-Hb and deoxy-Hb have different absorption spectra of light. The change in the absorption is converted to the change of oxy-Hb and deoxy-Hb using the modified Beer-Lambert Law (MBLL) (Scholkmann et al. 2014). Change in hemoglobin is a proxy for neural activation since an increase in oxy-Hb is associated with an increase in cognitive activation (Ferrari and Quaresima 2012; Buxton et al. 1998). Oxy-Hb usually has higher amplitude than deoxy-Hb and is more sensitive to cogntive activates (Hu and Shealy 2018).

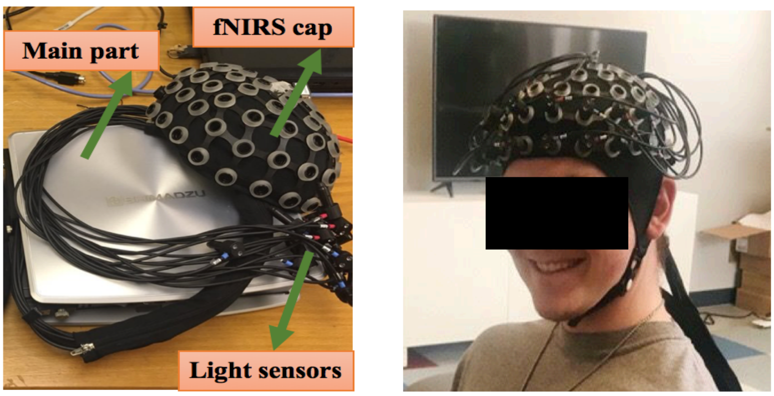

Figure 2: A fNIRS machine and cap

Research in cognitive neuroscience suggests that the prefrontal cortex (PFC) is a dominate region associated with decision-making processes (Hu and Shealy 2018). More specifically, sub-regions in the PFC are associated with detailed cognitive fucntions when decision-making under uncertainty. The dorsolateral prefrontal cortex (DLPFC) plays a critical role in cognitive flexibility and control (Kaplan et al. 2016; Mars and Grol 2007). The cognitive control function of the DLPFC is implicated in the modulation of risk attitudes (Schonberg et al. 2011). Previous research found suppressed activation in the DLPFC resulted in increased risk-seeking behaviors (Fecteau et al. 2007). In other words, higher activation in the DLPFC can be associated with cognitive control and higher aversion to risk. Another regions sensitive to risk altitude is lateral PFC and risk can increase the activation in this region for risk-seekers but reduce that for risk-averse participants (Tobler et al. 2009). A previous fMRI study found that DLPFC is correlated with the subjective value in the computation of willingness to pay (WTP) (Plassmann et al. 2007). The orbitofrontal cortex (OFC) also contributes to valuation and uncertainty processing (Plassmann et al. 2007). Risky decisions elicited higher activation in the OFC than in the DLPFC, while the activation pattern is opposite when handling ambiguity (Krain et al. 2006).

RESEARCH QUESTIONS

The aim of this research is to construct a better understanding of the cognitive barriers that limit more green infrastructure by measuring the cortical activation when making decisions about storm water infrastructure. The specific research questions include:

(1) What are the judgements about green and grey infrastructure solutions?
(2) How do patterns of cortical activation in the prefrontal cortex change when making judgements between green and grey infrastructure?

The hypotheses are that green infrastructure is perceived with higher uncertainty and participants have less willingness to pay for green compared to grey infrastructure. Correspondingly, when making judgements about the level of uncertainty associated with green infrastructure, engineering students, who are assumed as risk averse (granted more risk seeking than likely professional engineers) in financial and career domains, are expected to show increased activation associated with self-control and risk averseion. When rating their willingness to pay, these participants are expected to have reduced activation associated with subjective value for green infrastructure.

METHODS

A mobile fNIRS machine was used to measure change in cortical activation in the PFC when civil and environmental engineering graduate students made judgements and decisions in storm water infrastructure design scenarios. Three case studies detailing issues with current storm water (e.g. excessive storm water runoff, combined sewer overflow, and water pollution) in three cities were given and in each case two options, one green infrastructure and one grey infrastructure solution, was proposed. In the judgement phase, they rated the level of uncertainty associated with performance of the infrastructure with the rating scale from 0 (low) to 10 (high), and how much they were willing to pay for the infrastructure annually from \$0 to \$50 per linear foot, assuming the budget for construction came from community tax. In the decision phase, they made a selection based on their previous judgments for implementing either the green or grey solution.

The experiment design follows block design that gives participants a fixed time to complete each task. Figure 3 illustrates the experiment process. The experiment began with a 15-second rest period that aims to bring cortical activation of the participant to a baseline level. After the experiment, participants completed a short survey about their risk attitude in the domains of finances, leisure, career, health, and education (Ding et al. 2010).

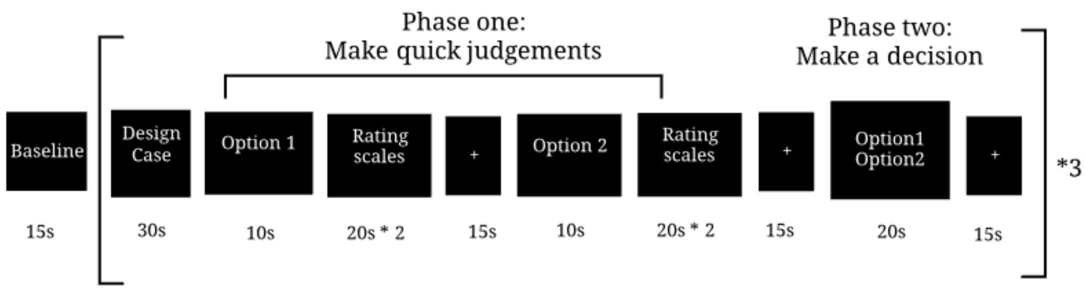

Figure 3: Experiment process

A total of 16 fNIRS sensors (eight light sources and eight receivers) were placed along the prefrontal cortex (PFC) as Figure 4 shows. The combination of a light source and an adjacent receiver is a channel. In total these sensors form 22 channels. Head measurement and the alignment of cap position to international 10-20 system was conducted to place the channels in the pre-designed locations. These channels can capture the BOLD response in the brain regions including DLPFC, OFC, lateral PFC and medial PFC.

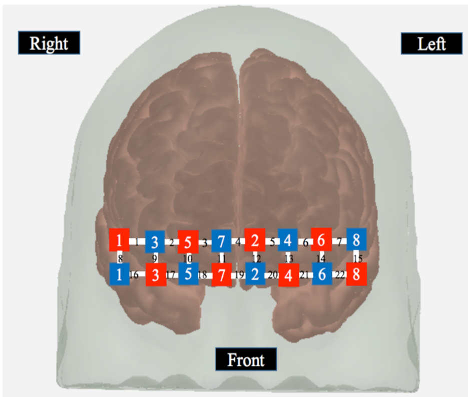

Figure 4: Placement of sensors
(Red labels are light sources and blue ones are receivers; links between sensors are channels that record BOLD response)

In the behavioral data, rating scores about uncertainty and willingness to pay for each participant were averaged among the three cases. Raw data of BOLD response was processed with a bandpass filter (a third-order Butterworth filter) of 0.01Hz – 0.2Hz to remove high-frequency instrumental noise and low-frequency physiological noise. An independent component analysis (ICA), using a coefficient of spatial uniformity (CSU) of 0.5, was conducted to remove motion artifacts. The choice of these parameters in data processing is based on prior research (Naseer and Hong 2015; Sato et al. 2011). In BOLD response, only oxy-Hb was analyzed and reported. Oxy-Hb for each participant was also averaged among the three cases and the mean value over the period of each rating scale was calculated for further analysis.

RESULTS AND DISCUSSION

The data collection is still on-going. In total, twenty engineering students will be recruited to participate. Six graduate students have participated in the experiment to date and the preliminary data analysis shows promising results about behavioral difference and corresponding neuro-cognitive patterns of activation in the prefrontal cortex (PFC) when making judgements about green and grey infrastructure.

Judgements about Green and Grey Infrastructure

All participant perceived higher uncertainty associated with green than grey infrastructure. A paired t-test finds significant (t=5.35, p=0.003) difference in their judgements about uncertainty with a large effect size (Cohen's d=2.56). But in contrary to the hypothesis, their willingness to pay for green infrastructure is higher than grey infrastructure. The difference is also significant (t=2.69, p=0.043) with a large effect size (Cohen's d=1.69). Figure 5 illustrates the difference in their judgements about green and grey infrastructure.

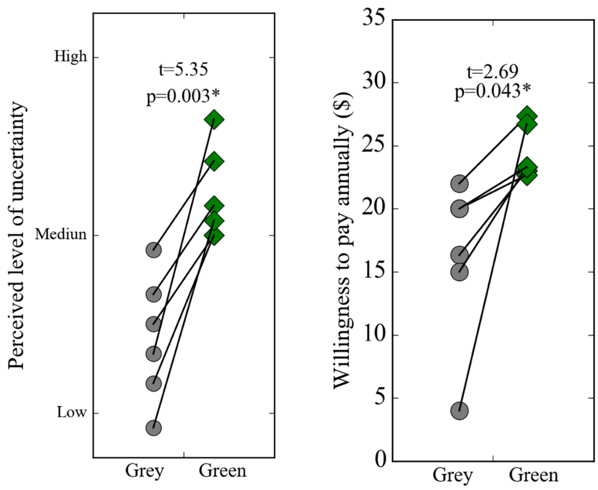

Figure 5: Differences in the judgements about uncertainty (left) and willingness to pay (right) between grey and green infrastructure

Decision-makers might be averse to higher uncertainty of green infrastructure, but they perceived green infrastructure as more valuable than grey infrastructure. A possible explanation for their higher willingness to pay for green infrastructure is that recruited graduate students have experience with sustainable design so that they value green infrastructure more than other stakeholder groups like the general public or professional engineers working in the industry.

Noticeably, the contradicting factors of uncertainty and value make it hard to predict their final decision between green and grey infrastructure. This also raised a new question about relative weights of these two factors contributing to final decisions about storm water infrastructure. A sample size of six is too small to compare the number of green or grey infrastructure in final decision. After completing data collection from all participants, a regression model will be developed to statistically describe the impacts of uncertainty and willingness to pay on their decision outcomes.

Cortical Activation When Making Judgements

When rating the level of uncertainty for green infrastructure, as Figure 5 illustrates, all participants showed reduced activation in Channel 8, located in the lateral prefrontal cortex of the right hemisphere, in comparison to rating for grey infrastructure. A paired t-test indicates the difference is significant (t=2.3, p=0.021). In contrast, in Channel 2 located in the right dorsolateral prefrontal cortex (DLPFC), five out of six participants had higher activation when rating uncertainty for green than grey infrastructure. Understanding the underlying regions of the brain that contribute to decision outcomes provides an opportunity not only to describe judgements about uncertainty or willingness to pay but to predict decision outcomes based on the level of cognitive activation observed in the brain. Future interventions can then work to change these levels of activation and measure their effect on decision outcomes. In other words, this new type of objective data provides a basis to test future interventions.

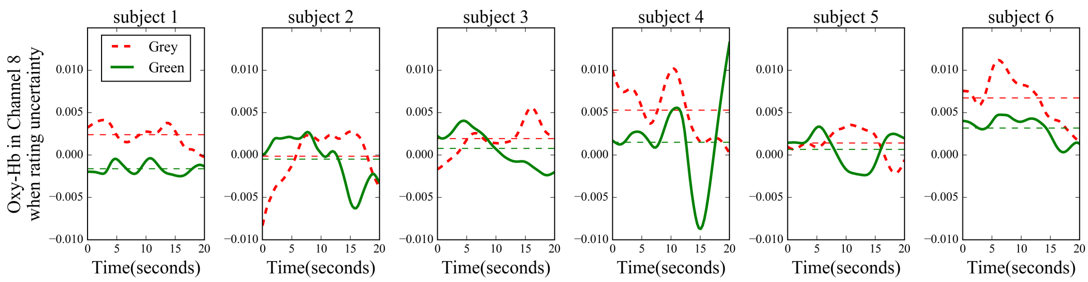

Figure 5: Oxy-Hb when rating the level of uncertainty for green and grey infrastructure

As mentioned, the behavioral result about willingness to pay is opposite to the hypothesis. Five out of six participants had higher activation in Channel 2 (right DLPFC), Channel 6 (left DLPFC), Channel 17 (right orbitofrontal cortex, OFC), and Channel 21 (left OFC). But the differences were not significant, likely due to the small sample size. Figure 6 indicates the oxy-Hb difference in Channel 2 that five participants (except subject 6) showed higher mean values and peak amplitudes in the change of oxy-Hb, and their activation were also sustained for a longer period of time. Previous neuroeconomics research found that subjective value in the willingness to pay computation is positively correlated with the activation in the right DLPFC and right OFC (Plassmann et al. 2007). In this study when rating willingness to pay for green infrastructure, the higher activation in the OFC and DLPFC predicted that participants spent more cogntive efforts and assigned more value to green infrastructure in value computation. Therefore, an effective intervention that encourages more adoption of green infrastructure should be able to activate more

BOLD response in these regions and also increase subjective valuation for green infrastructure.

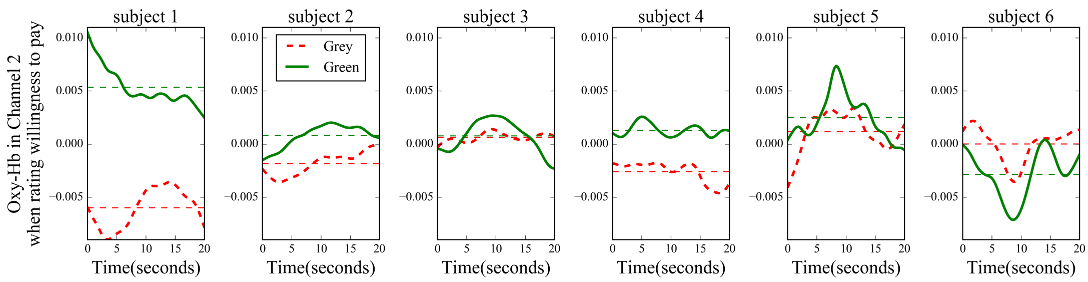

Figure 6: Oxy-Hb when rating willingness to pay for green and grey infrastructure

The survey about risk attitude indicates that all participants are risk averse in the domains of finances and career. When participants rated the level of uncertainty and green infrastructure was perceived with higher uncertainty, as expected, the activation in their DLPFC is higher because decision-makers tended to have higher aversion to the uncertainty and more functions of cognitive control were involved in the process. The reduced activation in the lateral prefrontal cortex (lateral PFC) is because higher uncertainty reduced activation in this region when the subject is risk-averse. This result is consistent with previous study by (Tobler et al. 2009). In other words, the reduction in activation in their lateral PFC might correlates with higher level of aversion to uncertainty.

Even though the behavioral and neuro-cognitive results about willingness to pay are contrary to the expected outcomes, a consistent correlation between behavior and brain is still supported by the results. Higher activation in the OFC and DLPFC, two regions that code subjective value and influence motor commands in willingness to pay computation, resulted in higher value assigned to green infrastructure than grey infrastructure. Correlation analysis between the activation and value did not yield a significant relationship with only six participants. A significant correlation might be found with a larger sample size in the following data collection.

CONCLUSIONS

This neuro-cognitive study provides explanations about the underlying mechanisms that support choice for green or grey infrastructure. Observed data at the neurological level is consistent with behavioral data about uncertainty, willingness to pay, and decision outcomes. The results indicate that green infrastructure is perceived with higher uncertainty and the cortical activation among decision-makers is also higher in the dorsolateral prefrontal cortex (associated with cognitive control and risk aversion). Engineering graduate students rated they were willing to pay more for green infrastructure than grey infrastructure solutions, and demonstrated higher cortical activation in the brain regions associated with subjective value computation. However, the question about how decision-makers weigh the factors of uncertainty and values and make choices is still unknown. Future study can explore the relative contribution of these two contradicting factors to the final decision outcomes about storm water infrastructure.

By measuring the neuro-cognition when making judgements and decisions about green and grey infrastructure, the results of this study provide a better understanding on the underlying mechanism of decision-making that influences long term outcomes about infrastructure. Future research can begin to test possible interventions to change behavior and cognition in the process of design and decision-making for green infrastructure. The results of this study also more broadly contribute to the understanding of engineering cognition and design of sustainable infrastructure, and can eventually contribute to more sustainable built environments.

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