Cognitive and physiological influences on energy related judgments

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**Cognitive and physiological influences on energy related
judgments**

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Cognitive and physiological influences on energy related judgments

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**Interdisciplinary Graduate School
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A thesis submitted to the Nanyang Technological University in partial fulfilment
of the requirement for the degree of
Doctor of Philosophy

2021

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

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Abstract

Reducing energy consumption remains a major focus for many countries for a combination of reasons including ecological, financial, and resource limitations. Strategies to reduce domestic energy consumption are increasingly focusing on socio-psychological and behavioural paradigms due to the pivotal role of behaviour in energy use. The aim of this thesis is to examine how a multidisciplinary visual perception and cognition approach to sustainability interventions may be applied to augment ongoing conservation efforts. Two types of intervention strategies: information provision and non-information multimodal sensory perception were investigated. The first study examines the effects of visual information communication parameters on information processing behaviour via eye-tracking methodology. Gaze behaviour towards real-world implementations of information feedback was influenced by different information elements and potentially semantic relatedness. The second study suggested perception of either water or energy utility to be incorrectly influenced by each other, which is influenced by task demands. The third study examined whether the multi-modal processing of different sensory inputs, i.e., visual (illumination colours) and thermal (room temperature) could interact to change occupants' thermal comfort. Participants' subjective evaluation of their thermal environment was significantly influenced by coloured illumination but the effect depended on the time of the day, suggesting a role of circadian mechanism. The findings open the possibility of reducing room temperature by altering the colour of the light. Overall, the present dissertation demonstrates the potential value of integrating cross-disciplinary visual perception and cognition approaches to address information communication assumptions and intervention needs in the sustainability literature.

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List of Abbreviations

ANOVA	Analysis of variance
AOI	Area of Interest
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BIS	Buying Impulsiveness Scale
CCT	Correlated Colour Temperature
COS	Consider-the-opposite
DA	Dominance Analysis
EEG	Electroencephalogram
fMRI	Functional magnetic resonance imaging
GHG	Greenhouse gas
GLMM	Generalized Linear Mixed Model
HHH	Hue Heat Hypothesis
IARC	International Agency for Research on Cancer
LED	Light Emitting Diode
LMM	Linear Mixed-effects Model
MB2	Microsoft Band 2
OECD	Organisation for Economic Co-operation and Development
PET	Positron emission tomography
TFT	Thin-Film Transistor

1 Introduction

1.1 Background and Context

Energy is key to virtually all aspects of human societal functioning and development. While the concept of resource conservation is thought to have begun as early as the use of energy itself (Wulfinghoff, 2000), inklings of modern conservation efforts started in the late 20th century in response to growing concerns over the increasing pressure on natural resources from human activities. During the energy crisis in the 1970s, the major industrial countries were faced with substantial petroleum shortages and soaring fuel prices – a rude awakening to the prevalent notion of abundance and continually diminishing energy prices during that period.

While early motivations of energy conservation were largely due to scarcity of fossil fuel supplies, wider realization and acknowledgement of the effects of unrestrained energy use on our environment have continued to spur conservation efforts today. In particular, the use of fossil fuels is noted to be associated in changes to the environment via greenhouse gas (GHG) emissions, including both gradual and extreme changes in weather (e.g., global environmental temperatures, sea-levels, heat and cold waves, droughts, floods). Such change not only poses a threat to a wide range of activities and normal societal functioning (e.g. agriculture, industry and commerce, social activities), but are also projected to increase in severity due to increasing pressure from global population growth trends (Añel, Fernández-González, Labandeira, López-Otero, & de la Torre, 2017; Behrens, van Vliet, Nanninga, Walsh, & Rodrigues, 2017; de Loë, Kreutzwiser, & Moraru, 2001; van Vliet, Sheffield, Wiberg, & Wood, 2016).

Moreover, the repercussions of anthropogenic climate change extend to the stability and resilience of existing energy systems as well. As a result of potential extreme temperature changes, energy demand is likely to change dramatically with increases in demands for cooling

expected in most parts of the world (IEA, 2013). Concurrently, energy generation and supply will face significant challenges such as reduced efficiency of thermal plants due to cooling limitations, changing conditions to generation from hydro and wind sources, as well as increased pressures on energy transmission systems (IEA, 2013).

Thus, mitigating anthropogenic climate change has recently shifted from being an issue in the peripheral to one of global importance within the last few decades (Cunningham & Lopreato, 1977; Milstein, 1977; M. E. Olsen, 1981; Samuelson & Biek, 1991). In addressing the issue of sustainability, we have been forced to re-examine the way we generate, consume and manage our resources. With domestic consumption accounting for a significant proportion of approximately 15-20% of total energy demand in OECD countries (Abrahamse, Steg, Vlek, & Rothengatter, 2005; Steg, 2008) and up to 40% of GHG emissions in developed countries (Hertwich & Peters, 2009), much research has been undertaken to minimize the impacts of individuals and their actions.

Notwithstanding technological limitations, human behaviour – one of the greatest drivers of climate change – poses a key challenge for sustainability efforts. Increasingly, a number of studies in domestic energy conservation have adopted a behavioural approach (e.g. Abrahamse et al., 2005; Allcott, 2011; Richetin, Perugini, Mondini, & Hurling, 2016; Shen, Sun, & Lu, 2017; Wolters, 2014), owing in part to findings where behaviour is revealed to account for a significant proportion of consumption variance. For instance, consumption differences of up to several times were observed between participating households – even within identical buildings or with supposedly efficient technologies and building design (Chen, Delmas, Kaiser, & Locke, 2015; Guerra Santin, Itard, & Visscher, 2009; Midden, Kaiser, & Teddy McCalley, 2007; Steemers & Yun, 2009). Furthermore, behaviourally oriented strategies are relatively faster and cost effective at reducing and/or stabilizing consumption and emissions compared to other strategies, at little or no reduction in individual or household well-

being (Dietz, Gardner, Gilligan, Stern, & Vandenberg, 2009). Hence, it is necessary for ongoing sustainability efforts to focus on the improvement of behaviours related to energy consumption.

However, converging evidence from behavioural and brain sciences suggests that the human judgement system and information-processing systems are ill-equipped to identify the threats to our environment (Markowitz & Shariff, 2012; Sterman, 2008; Swim et al., 2011; Weber, 2006), potentially dampening reactions to the issue. Moreover, while behavioural efforts to improve sustainability have often focused on sociopsychological drivers of behaviour and intention, there is a lack of attention towards the role of human visual processing and perception and their role in the effectiveness of such initiatives. In the following sections, we review the existing literature on energy behaviours, the dominant approaches and interventions, as well as the available literature on visual information processing.

1.1.1 Energy Behaviour: Literature Overview

Multiple definitions of behaviour currently exist depending on the discipline, field, theoretical framework, or study design. For example, classical behaviourism defines behaviours as actions that can be seen/observed, while in areas such as environmental and conservation education the concepts of behaviour include both overt and covert behaviours – those that can be observed (e.g. physical movement) and those that are private respectively (e.g. cognition and affect) (Heimlich & Ardoin, 2008). Within the energy conservation literature, discourse has revolved around a number of proposed dimensions with the dominant dichotomy of energy conservation behaviours falling into two categories: “*curtailment*” (usage) and “*efficiency*” (purchase) behaviours (Attari, DeKay, Davidson, & Bruine de Bruin, 2010; Dietz et al., 2009; Gardner & Stern, 2008; Karlin et al., 2014).

Broadly put, behaviours categorized under the “efficiency” (purchase) category are primarily associated with low-frequency occurrences, investment-related equipment(s),

products, or structural changes, such as the purchase and installation of compact fluorescent bulbs (CFLs), energy star appliances, and/or investing in structural or building envelop changes to the home (e.g., double-paned windows). Conversely, “curtailment” (usage) category behaviours are associated with adjustments or changes to high frequency, repetitive, and habitual usage-related practices, at low and/or no cost such as in turning off lights, unplugging of appliances, or reductions in appliance usage. Relevant behaviours relating to either dimension may also potentially interact with each other.

While the definition of specific behaviours in purchase behaviour research is relatively straightforward, in usage behaviour studies the term ‘energy behaviour(s)’ is often utilized relatively loosely (if explicitly defined at all). In particular, the measured outcomes of usage behaviour in many studies are often proximal references (e.g. reductions in overall energy consumption in kWh) which typically refers to the product of curtailment efforts across several distinct but related daily household energy-related activities (Abrahamse et al., 2005; Delmas, Fischlein, & Asensio, 2013; Fischer, 2008). The challenge of defining specific usage behaviour(s) observed within the literature stems from several factors, such as considerations for an objective measure that is general enough to account for the large heterogeneity in activities between individuals/households, or due to practical limitations such as the extreme technical difficulty/complexity and cost required to monitor each discernible behaviour.

Depending on the agenda, behaviours may also be classified under a hierarchical spectrum in accordance with the level of how conscious the individual is of each behaviour (i.e., reflexes, conscious behaviours, habits and routines). Specifically, *reflexive behaviours* refer to mechanical responses which are carried out continually without much conscious thought (e.g. smooth muscle activity), are intuitive, or are instinctive responses that are often involuntarily, species-specific and have little variability (Heimlich & Ardoin, 2008). In contrast, *conscious behaviours* require explicit conscious thought and effort and are often

associated with unfamiliarity in some form or another (e.g., contextual settings). Familiarisation of conscious behaviours through repetition allows for them to become learned responses, reducing the amount of conscious thought and effort required to initiate and execute and even eventually becoming reflexive in nature, such as in the involuntary reading of a text despite attempted focus on other attributes (such as colour) as demonstrated in a Stroop test (Stroop, 1935).

Unsurprisingly, as individuals have limited cognitive capacity to exert but are faced with a large multitude of different decision-making options in their daily life, many behaviours that are repeated eventually become automatic responses that are also known as *habits* (Becker, 1992). These *habits* may then subsequently be embedded in sequential chunks consisting of multiple *habits* known as *routines* as the complexity of life becomes increasingly demanding. Functionally, this development of autonomous *habits* and *routines* serves to prevent exhaustion of cognitive resources (Frank, 1987), preventing individuals from being overwhelmed, while freeing up attention to contend with the unfamiliar. Over time, the aggregation of *routines* and *habits* eventually dispositions responses towards a long-term tendency to respond in a certain direction or manner, in what is also termed a default action (Heimlich & Ardoin, 2008). This is similar to ‘default options’ in behavioural economics in which the decision maker will opt for pre-set courses of action that occur if the event of inaction (i.e., the decision-maker does not actively specify a decision) (Thaler & Sunstein, 2008). Whilst originally confined to motor or physical responses, the concept of *routines* and *habits* have since been expanded to also include cognitive, perceptual and affective responses.

To summarize, energy behaviours may be defined across multiple dimensions – such as the type of energy conservation behaviour (e.g., purchase or usage), the level of consciousness, as well as in the context of other behaviours. In reality, few energy behaviours are truly isolated, often being subject to multiple influences from various socio-psychological,

cultural, contextual and environmental factors that an individual may or may not be conscious of (Frederiks et al., 2015b; Heimlich & Ardoin, 2008). Moreover, most energy behaviours are also habitual or embedded in routines, with allowances for conscious modulation by the individual where necessary. To effect behavioural change, it would appear necessary to consider strategies that target the formation of reflexive behaviours such as habits and routines, as well as factors that lead to certain behaviours being sustained or extinct.

1.1.2 Socio-Psychological Theories, Frameworks and Paradigms

Attempts to comprehend the drivers of energy conservation behaviour have commonly involved efforts to examine and characterize the key socio-psychological determinants of individual-level differences in pro-environmental and residential energy behaviour. Numerous factors identified within the literature include situational factors within the external environment (such as contextual, structural and institutional factors), as well as more individual-centric attributes including norms, motivations, attitudes and values – all of which have been hypothesized to play a role in driving individual differences in conservation behaviour (Abrahamse & Steg, 2011; Costanzo, Archer, Aronson, & Pettigrew, 1986; Poortinga, Steg, & Vlek, 2004; Van Raaij & Verhallen, 1983; Wilson & Dowlatabadi, 2007).

In earlier studies, a social-psychological model of energy conservation was proposed to consist of two interacting groups of factors that can be broadly classified as psychological and situational. More specifically, psychological factors involve intrinsic aspects such as memory, cognition, judgement and perception while situational factors involve more extrinsic aspects involving variables such as disposable income, ownership of residence, skills relating to home improvement, as well as technology) (Costanzo et al., 1986). Subsequently, it was proposed that environmental behaviour is moulded by a range of attitudinal variables (e.g. behavioural norms, beliefs, other existing environmental and non-environmental attitudes), personal capabilities (e.g. literacy, social status, skills and financial capacity), contextual

factors (e.g. social norms and expectations, laws, policies), habits and routines (Stern, 2000). More recent studies have also since distinguished between multiple influences (both positive or negative) of pro-environmental behaviour, such as demographic factors (i.e. gender, age, education), external factors (e.g. institutional, social, cultural, and economical), as well as internal factors which encompass motivations, attitudes, awareness, values, emotions, locus of control and pro-environmental knowledge (Kollmuss & Agyeman, 2002). Other approaches have also proposed two distinct categories of factors affecting household-energy usage: micro-level factors (e.g. motivation, ability, opportunities) and macro-level factors (e.g. technological, economical, demographical, institutional, cultural) (Abrahamse et al., 2005).

Figure 1. Identified factors of influence on energy consumption and conservation behaviours.

(adapted from Frederiks et al., 2015b)

Examples of highly influential theories of conservation behaviour include the Value-basis theory of Environmental attitudes and the Value-Belief-Norm theory (Stern, 2000; Stern & Dietz, 1994; Stern, Dietz, Abel, Guagnano, & Kalof, 1999) – which postulates that values,

beliefs and personal norms influence pro-environmental behaviour; where norm-based actions flow from the acceptance of particular personal values, beliefs that things of importance to said values are under threat, and beliefs that the actions initiated by the individual are able to alleviate the threat, thus restoring said values. Another example is the Integrative model for behavioural prediction – the latest formulation of the Reasoned Action Approach (Fishbein & Ajzen, 2011) - which states that attitudes towards the behaviour, perceived norms and perceived behavioural control determines people's intentions and that the intention to perform a behaviour follows reasonably (not necessarily rationally) from specific beliefs individuals hold about the behaviour. Also, the model of responsible environmental behaviour – which views both the intention to act, as well as objective situational factors, as direct determinants of pro-environmental behaviour (Hines, Hungerford, & Tomera, 1987), with intention itself perceived as a summary of the interplay of cognitive and personality variables.

Also widely employed in the literature is the Norm-Activation model – a vested model explaining prosocial and altruistic behaviour as following from personal norms, of which is activated by four situational variables: problem awareness, ascription of responsibility, efficiency of outcome, and the ability to recognize the capacity of oneself to provide relief (Schwartz, 1977; Schwartz & Howard, 1984). Other notable cross-disciplinary frameworks include the Theory of affordances – a learning theory where the perception of possibilities for action (affordances) is thought to drive action and behaviour (Gibson, 1977, 2014b) (see Table 1 for a brief summary of notable frameworks, models and paradigms employed). More recently, the comprehensive action determination model (CADM) (Klöckner & Blöbaum, 2010) – drawing from theories such as the Theory of Planned Behaviour (Ajzen, 1991), the Norm-Activation model (Schwartz, 1977; Schwartz & Howard, 1984), the ipsative theory of behaviour (Tanner, 1999; Tanner, Kaiser, & Wöfing Kast, 2004), as well as the theoretical concept of “habit” (Triandis, 1979) – assumes that individual behaviour is directly determined

from intentional, situational and habitual influences, and indirectly from normative influences, with potential interactions possible between the four influences.

Table 1. Summary of prominent existing theoretical approaches to pro-environmental/ energy conservation behaviours within the literature.

Theoretical Framework/ Approach	Summary
Norm-Activation model (Schwartz, 1977; 1984)	Personal norms, awareness of consequences and ascription of responsibility predict pro-social intentions and behaviour.
Reasoned Action Approach (Fishbein & Ajzen, 2011)	Behavioural beliefs, normative beliefs, and control beliefs influence attitude towards behaviour, perceived norms, and perceived behavioural control respectively, which then determine intention and subsequently behaviour.
Theory of reasoned action (Fishbein & Ajzen, 1967)	Attitudes and norms predict and explain behavioural intention - the main motivator of behaviour.
Theory of planned behaviour (Ajzen, 1991)	Attitudes, subjective norms and perceived behavioural control predict intention and subsequently behaviour.
Value-Belief-Norm theory (Stern et al., 1999)	Pro-environmental behaviours stem from the acceptance of a movement's basic (e.g., particular personal) values, and from the belief(s) that things important to said values are under threat, in addition to the belief(s) that the individual's actions can help alleviate the threat and restore the values, such that they experience an obligation (personal norm) for pro-movement action.
Model of Responsible Environmental Behaviour (Hines et al., 1987)	Responsible environmental behaviour is predicted by both situational factors and the intention to act. Intention is predicted by the variables: action skills, knowledge of issues, knowledge of action strategies, and personality factors (including locus of control, attitudes, and an individual's sense of responsibility).
Theory of Affordances (Gibson, 1979)	Affordance theory studies the relations between abilities to perceive and act and environmental features.
Steg, Perlaviciute & van Der Werff, 2015	General 'framework' of sustainable energy behaviours consisting of 4-key issues: (1) identify and measure energy behaviours; (2) understand which factors underlie different energy behaviours; (3) design and test effects of sustainable energy behaviour interventions, (4) study factors affecting acceptability of energy policies, interventions and changes in energy systems.

To date, a plethora of different socio-psychological behavioural theories and disciplinary approaches have since been examined within the extant literature (Abrahamse et

al., 2005; Berman, Shwom, & Cuite, 2019; Bird & Legault, 2018; Corral-Verdugo, Frías-Armenta, Pérez-Urias, Orduña-Cabrera, & Espinoza-Gallego, 2002; Delmas et al., 2013; Jorgensen, Martin, Pearce, & Willis, 2014; Karlin, Zinger, & Ford, 2015; Koop, Van Dorssen, & Brouwer, 2019; Steg, Perlaviciute, & van der Werff, 2015). However, none have been unanimously accepted across the literature, with reviews noting multiple limitations such as the over- and underestimation of importance regarding characteristic effects. For instance, the TPB, whilst focusing on intentions, severely underestimates the role of objective situational constraints, facilitators, habits and personal norms. Conversely, the NAM places emphasis on personal norms but neglects the effects of habits, intentions, attitudes and situational context. For both TPB and NAM, studies have also indicated limited predictive ability with regards to certain behaviours such as repetitive behaviour (e.g. Klöckner, Matthies, & Hunecke, 2003). Other limitations also include the reduction of situational influence on behaviour and perceived behavioural control. Though empirical evidence has suggested some factors to be better predictors of energy behaviours than others, such findings are noted to be inconsistent (Frederiks, Stenner, & Hobman, 2015a). Other critiques include being able to account only for a scant amount of observed behavioural variance (Bamberg & Möser, 2007; Gram-Hanssen, 2014), or that there is poor support for the generalisability of such theories/models in the findings of cross-cultural analyses (Stenner & Nwokora, 2015), suggesting that such frameworks may have declining utility in future analyses.

While a single integrative model that is applicable to all behavioural situations may seem ideal (Klöckner & Blöbaum, 2010; Wall, Devine-Wright, & Mill, 2007), such models are typically complex, requiring more complex data (e.g. CADM and longitudinal data) or adaptation of the models to analyse the posited complex relations between different variables. Potentially, one reason for the difficulties of various behavioural paradigms and explanatory attempts may be that the drivers of pro-environment attitudes and energy conservation

behaviour are far too numerous, complex and impractical for any lone attempt at a universal parsimonious model or framework. However, such invocations of the issue of complexity may also lead to the fallacious perception that greater explanatory power can be achieved by piling on more variables into existing theories of the current paradigm. Others have reasoned that as all models show limitations in other domains, the focus should be on identifying and using specific models that perform best depending on the domain (Lindenberg & Steg, 2007). Regardless, empirical inconsistencies on which identified factors are better predictors of energy consumption may potentially be an artefact of sorts. In particular, due to the scarcity of well-designed, appropriate and rigorous testing of causal relationships within proposed frameworks in many empirical studies (Abrahamse et al., 2005).

1.1.3. Behavioural Interventions

The implementation of influential socio-psychological, theoretical models in formulating behavioural change strategies within the last few decades has since resulted in a wide variety of different intervention strategies (Abrahamse et al., 2005). These efforts, designed to effect behavioural changes via the modulation of associated factors (e.g. incentivizing desirable behaviours and punishing undesirable ones, activating norms, influencing attitudes) has since mustered a virtual hegemony in multiple domains (e.g. research and policies) (Abrahamse et al., 2005; Darby, 2006; E. Ho, 2015; Steg & Vlek, 2009).

In general, most existing socio-psychological intervention approaches targeting voluntary behavioural change (i.e. efficiency and curtailment) may be classified as antecedent (e.g. commitment, goal setting) or consequential (e.g. feedback information and rewards) (Abrahamse et al., 2005; Steg & Vlek, 2009) – both of which may be combined for greater effectiveness (Abrahamse et al., 2005). Antecedent intervention approaches are generally designed to target one or more attitudinal factors prior to engaging in energy conservation

behaviours, while consequential intervention aims to guide subsequent behaviour through influencing the perceived significance of prior (energy usage) behaviour.

Of the many intervention strategies devised, the use of information is most widely utilized: as an antecedent intervention including workshops (information provision paired with another intervention method), modelling (based on information of positive examples of energy conservation behaviour), home audits (typically where tailored information regarding energy usage behaviour is given to avoid overloading of general information), mass media campaigns; or as a consequential intervention, such as in the provision of feedback. This information-centric approach relies on the central tenet of all behaviourist theories of stimulus and response, being often cited as a means to address the problematic ‘doubly invisible’ nature of energy by making energy consumption more ‘visible’ and accessible (Delmas et al., 2013; Fischer, 2008).

For example, the provision of feedback of energy usage as numerical values (representing the historical amount of energy consumed by a household for a particular period or duration) is posited to allow for the association of behaviour(s) with certain outcomes (e.g., consumption levels, cost incurred), prompt (motivated) users to learn about their own energy habits, address information deficits on energy usage (Buchanan, Russo, & Anderson, 2014) and increase the ‘visibility’ of energy overall. Improving feedback on various parameters such as better temporal resolution (i.e., feedback is given more immediately relative to the behaviour), higher frequencies (i.e., given more often), better ease of accessibility, higher specificity and less aggregation (e.g., information for specific appliances/activity relative to for the whole house/building) has been found to reduce consumption by 5% to 20% (Darby, 2006; Fischer, 2008).

Information provision is also thought to effect behavioural changes in multiple ways, such as addressing information asymmetries (i.e., identifying and/or increasing knowledge about existing energy problems), as well as imparting knowledge about possible solutions or

methods of recourse. The provision of information may also effect changes in behaviour by changing perceptions, such as enhancing the availability or accessibility of actions, saliency of existing issue(s), modulating intrinsic factors (e.g., influencing motivation, attitudes, values and/or norms), and/or changing the contextual perspectives in how such issues are viewed (e.g., priming energy conservation to be associated with altruism and trust, environment and health). For instance, with regards to purchase behaviours in the energy economics literature, information is employed as a strategy to address the energy efficiency gap phenomenon – where firms and households do not seem to improve energy efficiency via investment in new efficient technology, despite it being cost-effective for them to do so. This phenomenon is thought to be the result of people holding implicit high discounts on energy saving rates that are far above interest rates in the capital markets (Hausman, 1979), potentially because of poor/incomplete information (Allcott & Greenstone, 2012; Gillingham & Palmer, 2014; Newell & Siikamäki, 2014; Sanstad, Roy, & Sathaye, 2006; Tietenberg, 2009).

However, despite the promising value of informational interventions in reducing energy consumption domestically, there are still many gaps within the literature that have caused the effectiveness of such interventions to be questionable. For instance, there are multiple reports of wide variations in the measured effectiveness of informational strategies on energy conservation behaviour, ranging from as much as a 55% reduction in consumption to a problematic 18.5% increase (Allcott, 2011; Delmas et al., 2013). Reviews of intervention studies aimed at household energy conservation have also since highlighted a number of critical concerns within the literature (Abrahamse et al., 2005).

One potential reason for the intervention effectiveness may be inherent limitations in the underlying theoretical model and/or framework. Approaches may differ in aspects such as how measures of behaviour are operationalized, to how predictors are ‘allowed’ to interact in conceptual models and statistical analyses. For instance, early linear models of environmental

behaviour were based on rationalist linear progression of environmental knowledge, which supposedly then led to environmental awareness and concern and subsequently pro-environmental behaviour (Figure 2). Such rationalist models, which have their roots in neoclassical economic models of fully rational decision and behaviour (e.g. Burgess, Harrison, & Filius, 1998), have since been demonstrated to be problematically constrictive and insufficient in predicting actual behaviours. Similar conclusions have also been drawn in related instances of attempted behavioural change, such that merely providing information does not necessarily lead to rational decisions to reduce energy consumption, suggesting that the postulated linear rationalist relationship does not exist (Hargreaves, Nye, & Burgess, 2010).

Figure 2. Early models of pro-environmental behaviour adapted from Kollmuss & Agyeman, (2002).

Some other issues observed include the unclear or even lack of specification of the exact intervention contents, ambiguity regarding provided information's relevance (to either energy problems, energy conservation measures, or both), the confounding use of a combination of multiple strategies (with little to no systematic evaluation or information regarding each individual contribution and/or effects), instances of very small sample sizes (with large within-group variances) and insufficient statistical power, sampling biases – such as self-selection (e.g. motivation) bias in households who willingly volunteered to participate in such studies, low effect sizes, a lack of available statistical information to calculate effect sizes, inconsistent indicators used to test the effectiveness of interventions and potential issues with subjective self-report measures. The durability of behavioural change is also important

for sustainability interventions. However, relatively little is known about the robustness and long-term effects of interventions due to the time, resources and other constraints required to monitor behaviour over longer periods of time (Abrahamse et al., 2005; De Young, 1993; Dwyer, Leeming, Cobern, Porter, & Jackson, 1993).

Equally problematic but understudied is the large methodological variety in the implementation of interventions – even within similar mediums. For instance, the same feedback information that is delivered to the recipient on a paper printout can vary in whether it is represented in numerical or textual forms, presented categorically (e.g. happy or sad cartoon faces) (Schultz, Nolan, Cialdini, Goldstein, & Griskevicius, 2007), or as diagrammatical (e.g. bar, pie, or line charts) formats. Although such differences in information communication studies have been documented to have significant effects on cognition and decision making, such as in accuracy assessments, information utilization patterns and interpretation (Peebles & Cheng, 2003; Sanfey & Hastie, 1998; Shah & Freedman, 2011) (also see section 1.1.5), the assumptions of the choice of specific visual communication parameters and their potential impact on intervention effectiveness are rarely ever discussed.

1.1.4 Nudges/Choice architecture and behaviour

In light of the limitations of traditional rationalist models of decision making and behaviour, bounded rationality – a conception of rationality that accounted for human cognitive limitations – was first posited by Herbert Simon (Simon, 1955, 1957) in his seminal call to replace the perfect rationality assumptions in neoclassical economic theories. Subsequent work in judgement and decision making by Kahneman and Tversky's in the 1970s and 1980s helped further demonstrate that contrary to existing economic theories of decision making at the time, human behaviour often departed from the predicted boundaries of classical expected utility theory, heightening the influence of psychological principles and ideas within the field of decision making and cumulating in the formation of the field of behavioural economics

(Kahneman, 2011; Thaler & Ganser, 2015; Tversky & Kahneman, 1974). Since then, a growing body of literature has revealed human decision-making and behaviour to be typically guided by a low level of cognition and habits as evidenced by demonstrations of a characteristic susceptibility to turn to various heuristics, observations of typical a-rationality and suboptimal decisions (Maréchal, 2010).

This body of work has since yielded the behavioural change strategy known as ‘nudging’ or ‘choice architecture’, which targets the inherent choice phenomenon (Thaler & Sunstein, 2009). For example, by virtue of instituting consumers’ participation in the smart grid as the default option while requiring individuals to actively opt-out, participation rates were observed to be significantly increased (Broman Toft, Schuitema, & Thøgersen, 2014)., Relatively inexpensive and less invasive compared with traditional direct interventions, emerging literature on the instrumental effectiveness of nudging as a policy tool (Schubert, 2017) and a growing consensus that nudges are able to complement other methods of intervention (Lehner, Mont, & Heiskanen, 2016) have all indicated nudging to be suitable as a sustainability intervention. Previous instances of nudging usage have shown the strategy to be effective in encouraging eco-friendly behaviours, such as the use of commitment and signalling to increase towel-reuse behaviour of guests in hotels (Baca-Motes, Brown, Gneezy, Keenan, & Nelson, 2013) and the use of defaults to promote domestic uptake of green energy (Ebeling & Lotz, 2015; Momsen & Stoerk, 2014).

Conceptually, nudging is based on the idea that subtle and indirect suggestions, including the way the choices are presented (“choice architecture”), can influence the motives, incentives and decision making of people, as opposed to direct instruction, legislation or enforcement. Nudges employ a variety of psychological mechanisms such as by informing (e.g. provision of more comprehensible information), or by the introduction of non-informational influences (e.g. making certain choices more prominent or salient than others) into the decision

making process (Thaler & Sunstein, 2009). Distinct from prospective theory in economics that describes how people evaluate risk due to cognitive limitations, nudging focuses on identifying heuristics and how decision making and behaviour can be influenced. Instances of nudging include the use of social proof heuristics: where an individual's tendency to look towards the behaviour of others to guide their own behaviour was found to be effective in influencing healthier food choices (Cheung, Kroese, Fennis, & De Ridder, 2017), changing the layouts and features of different environments, reminding people about their own choices, as well as the framing effect – where the way a choice is presented (e.g. highlighting the positive or negative aspects of the same decision) can result in distinctly different changes in behaviours (Lehner et al., 2016).

It is theorized that nudges work in situations where decision makers are subject to limited attention, resulting in decisions and behaviour construed as not fully rational (Löfgren & Nordblom, 2020). As the optimization of a decision (i.e., well-informed, utility-maximizing) is cognitively demanding and the outcome of a decision typically being subject to some degree of uncertainty, individuals may instead make a choice inattentively or rely on some heuristics (e.g., choosing using intuition, habits, the first or last option on a list, acting on cues such as reminders, or even making a random draw) (Gigerenzer & Gaissmaier, 2011), thus making their decisions and behaviour susceptible to influence by nudge interventions. This theorized mechanism of nudging references the dual-process theory of two systems underlying human decision making and behaviour: System 1 and System 2 (Epstein, 1994; Kahneman, 2003). Where System 1 operates automatically and quickly with little to no effort, and often with no sense of voluntary control, System 2 operates reflectively, requiring the allocation of attention to effortful mental activities and being often associated with a sense of agency. (Epstein, 1994; Kahneman, 2011; Löfgren & Nordblom, 2020).

However, despite its' potential as a complementary intervention tool and effectiveness in changing behaviour, the ethicality of using nudges are a recurring source of concern and critique within the literature – having been likened to soft deception or argued as a form of libertarian paternalism which grants institutions (e.g. governments) too much power (Broman Toft et al., 2014; Schubert, 2017). The subconscious nature of influencing behaviour change in nudging may also be viewed as manipulative and an infringement on personal autonomy, potentially resulting in a backlash in individuals' general perception of institutional and policy efforts. Other criticisms also include the inherent passive nature of the intervention; where due to the onus of effecting change being placed upon others (e.g., policy makers), the lack of engagement on the individual's part results in a lack of change in intrinsic factors such as attitudes and values. Thus, such approaches are posited to only be effective in the short-term, or as long as policies take such issues into account and act on them on the individual's behalf. Moreover, despite having been previously implemented in energy policies, nudging interventions are commonly applied unsystematically and sporadically (Lehner et al., 2016), sometimes resulting in issues such as incomprehensible electricity bills in spite of known issues with information overload and the importance of framing (Darby, 2010; Fischer, 2008).

Nevertheless, with careful implementation, some of the aforementioned concerns may be avoided. For instance, literature on potential feedback and forward mechanisms suggests that actions, as guided by nudges, may instead prompt individuals (possibly via processes such as cognitive dissonance) to rationalize and internalize values that are congruent with the actions, leading to changes in attitudes and durable behavioural changes (Ross et al., 2016). Other issues such as how different factors, multiple nudges, or nudges and socio-psychological interventions may interact together would instead require more usability and evaluative studies to understand.

1.1.5 Visual Perception and Information Processing

While experiences in the real world are largely visual, with information communication typically consisting of both pictorial and textual information, there are few relevant studies within the sustainability literature that have focused on the effects of information processing on sustainable usage/efficiency behaviour interventions and outcomes. To better understand why it is important and how such parameters may influence information perception and behaviour, the current section aims to provide a brief review of cross-disciplinary literature on visual information processing and perception.

Within the literature there are two dominant theoretical approaches to the study of visual perception: the ecological approach (Gibson, 2014a) which concerns processing of only sensory stimulation information and the constructive-inferential approach (Boring, 1946; Epstein, 1973; Rock, 1983; 1997) which in contrast, pertains to the processing of information past that of sensory stimulation (Epstein, 1995; Norman, 2002). While the ecological approach was observed to be excellent in analysing stimulation that reached an organism, it needed to be complemented by an understanding of the processes which the core (the basic sensory data/input from the object one is perceiving) is modified or corrected by the context (all other sensory information/input aside from the core) – which was the scope of the constructive-inferential approach (Haber, 1985.; Norman, 2002). Subsequent research findings on animal models (Ingle, 1973; G. E. Schneider, 1969; Gerald E Schneider, 1967; Trevarthen, 1968) suggested visual analysis to be carried out by two systems (the ‘what’ and ‘where’ modes/streams), which eventually gave rise to the study of the ventral and dorsal visual systems – both of which analysed visual inputs, albeit for different purposes. Specifically, the former involved object recognition and identification while the latter was identified to be involved with the egocentric transformation and usage of such information (Goodale & Milner, 1992).

Differences between both systems also exist along other dimensions, such as the ventral system being better at discerning fine details, has processes that are typically more conscious and is often more object-centric. Conversely, the dorsal system considered to be faster in general (with exceptions including text identification and reading), more spontaneous and typically more egocentric in perspective. Both systems may operate together under certain circumstances: such as when visually identifying an object moving towards oneself, the ventral system recognizes its identity and size while movement is processed by the dorsal system (Norman, 2002). Visual information processing can hence be organized accordingly to the differences in the two systems: with object processing predominantly focused upon recognizing and interpreting what is being perceived, while spatial processing generally focuses upon movement and transformation relative to the self.

Concepts associated with visual information processing generally include: colour, shape, complexity, aesthetics, text and visual information. Colour may be examined from its' three basic properties: hue – the pigment of colour (e.g., red, green, blue), chroma – the intensity or saturation indicating the amount of pigment present, and lastly value – which refers to how light or dark a colour appears (Thompson, Palacios, & Varela, 1992). These individual properties may each have distinct perceptual effects at even the most basic level, such as what might be perceived as gold may appear as blue or black to another, depending on factors such as assumptions of illumination/ source of lighting).

Colour has also been documented to affect both inferential and affective processes. For inferential processes, the effects of colour can be both indirect or direct. In particular, effects that are direct are based on existing associations between a colour and concepts that are dependent on an individual's history, and are thought to result in specific inferences upon exposure, such as perceptions of luxury and subsequently larger tipping behaviour in response to the use of gold-coloured service props in the context of a restaurant (N. Y. Lee, Noble, &

Biswas, 2018). Mere presence of colour, however, does not necessitate such effects to manifest such as in the case of pre-existing motivations and prior exposure (e.g., to images that are more resource-demanding stimulations), but are likely to occur when there is a lack of motivation to process, or that the individual was exposed to low-resource demands (e.g. functional oriented ads) (Meyers-Levy & Peracchio, 1995).

Colour is also well-established to influence affect and arousal (Gorn, Chattopadhyay, Yi, & Dahl, 1997), with adverts using higher-value (lighter) colours being observed to be more liked, potentially via mediating effects of feelings of relaxation or conversely by excitement. For instance, the background colour of a web page was noted to influence perception of download speeds, even spilling over to the site's ratings of likeability (Gorn, Chattopadhyay, Sengupta, & Tripathi, 2004). While the isolated use of colour is rare, the effects of colour in conjunction with other sensory modalities have been the interest of several recent studies (Hagtvedt & Brasel, 2016) although the reasons for such effects are still not wholly understood.

Though not directly related to the present thesis, visual shapes are also noted to have an effect on individuals' preferences and behaviour (Benjafield, 1976; McManus, 1980). In addition to potential effects on attention, shapes may also convey meaning (Pieters & Warlop, 1999), although the relevant research is still relatively scant across the literature and the exact reasons are unclear. Within the literature, studies have found preferences for shapes to often be associated with a range of ratios (Raghubir & Greenleaf, 2006), such as perceptions of quantity being influenced by packaging shape (Folkes & Matta, 2004; Krider, Raghubir, & Krishna, 2001; Raghubir & Krishna, 1999). In the case of logos, shapes that communicate certain information have been observed to influence behaviour; such as exposure to an 'unstable' triangular or square logo (standing on its' vertex) relative to stable looking logos (resting on its base/face) was found to increase participants' consumption of products that are thematically

associated with safety (e.g. smoke detectors, personal disinfection agents, or even insurance), (Rahinel & Nelson, 2016), suggesting a role of prior associations in such effects.

Moreover, the complexity of a visual object may also influence perception, such as in pairing an image of a steel ball with a congruent or incongruent brand name (Janiszewski & Meyvis, 2001). While initial exposures revealed participants to show a lower preference for the incongruent condition, repeated exposure increased relative preferences for it, suggesting an effect that is time-dependent. Furthermore, cultural differences may also influence preferences for complexity (Henderson, Cote, Leong, & Schmitt, 2003).

With regards to aesthetics, its impacts have been noted to be highly salient in areas such as marketing communications where research interest has delved into attention, eliciting inferences, and on behaviour. Basic elements such as fonts and typeface have been noted to influence attention, impressions, and elicit preferences and behaviour. For instance, the use of an incomplete text logo (which letters were partially obscured) resulted in associations of creativity, while conditions exposed to a complete typeface logo associated the company with feelings of greater trustworthiness (Hagtvedt, 2011). Even in contexts where aesthetics is presumed to be of low relevance, such as in the appearance of a financial document, the use of aesthetics was found to influence stock evaluation and behaviour – with relatively higher valuation assigned to a company when its' annual reports were aesthetically superior, even with experienced investors as subjects (Townsend & Shu, 2010). Such effects were only corrected under conditions where the aesthetics of the report was made salient to participants.

Several potential explanations regarding the mechanisms of aesthetics have been proposed in the literature. Aesthetics may elicit inferences based on past associations, such as where appealing aesthetics are observed to encourage donations to a charity when perceived to have no cost implications, while higher cost implications or increased perceptions of organization waste reduced/discouraged donations. Aesthetics may also impact judgments via

elicited feelings (Kumar & Garg, 2010), such as in empirical findings of increased activation of reward centres in the brain in response to exposure to aesthetically pleasing stimuli (Reimann, Zaichkowsky, Neuhaus, Bender, & Weber, 2010). The effects of aesthetics may also stem from the implications on one's sense of self (Townsend & Sood, 2012), such as in public displays of preferences (i.e. the purchase of aesthetically appealing products), where conditions with self-affirming tasks reduced the likelihood to choose a highly aesthetic product, or that consumers had higher openness to counter-attitudinal arguments after the purchase of products with good design. However, it is interesting to note that people generally have low awareness and accuracy of their preferences for aesthetics (Buechel & Townsend, 2018), with observations of incorrect predictions of irritation, satiation and liking of designs with different arousal values across durations.

Other parameters that are important to consider include the size of an object – which is generally positively associated with the amount of attention. The use of pictures, relative to text, have been observed in studies to elicit more attention, facilitate the communication of more information, improve memory recall (i.e. the picture superiority effect) (Childers & Houston, 1984), although the effect on different aspects of communication with regards to attention is still currently unclear. Although larger sizes tend to attract attention, this effect is dependent on the type of stimulus (Pieters, Wedel, & Zhang, 2007; Wedel & Pieters, 2008) and multiple other parameters (Peschel & Orquin, 2013). Other studies within the literature have reported such differences in only specific segments, suggesting the effects of text and/or picture size to be dependent on the context of presentation and individual differences (Goldberg, Probart, & Zak, 1999; Rosbergen, Pieters, & Wedel, 1997). Moreover, the size of one element influences the amount of attention individuals confer to other elements (Pieters & Wedel, 2004); such as increased text size elements not impacting the amount of attention given

to pictures, but instead reducing attention to other brand elements –even when brand elements had their size increased.

Although greater attention is thought to enhance memory, this appears to be dependent on the type of information that attention is given to, as well as the processing strategy used. For instance, in both immediate and delayed-recall tasks, a picture superiority effect occurred for pictorial stimuli (advertisements) in both tasks when the processing strategy involved appearance-related adjectives (e.g. shape), in contrast to only improved immediate recall in a semantic-processing strategy (towards adjectives such as “strong”) with verbal only stimuli (Childers & Houston, 1984). Thus, the manner of visual information processing may also be a critical factor in understanding the implications of such effects on memory.

1.2 Motivations & Thesis Structure

To summarize, there is a pressing need to act sustainably as the growing demands for energy are likely to intensify. To address these concerns, interventions designed to induce behavioural change have been the subject of interest to many researchers. While a rapidly growing body of theoretical and empirical work has suggested energy behaviour interventions to be effective, there is also mounting evidence of unresolved issues within the extant literature. In particular, reviews have noted problematic inconsistencies in intervention effectiveness. These large variances are proposed to stem from a number of causes including a lack of rigorous systematic evaluations and methodological heterogeneity. Potentially, such causes may be due to a severe lack of consideration of the biological constraints that limits people’s ability to be influenced by intervention strategies that capitalize upon processes that dictate their experiences of their world.

In reviewing the literature, it seems timely to consider the need for more interdisciplinary approaches in the field of sustainability and behaviours. The idea of integrating theories, concepts, techniques and data from a diverse body of knowledge (Porter,

Roessner, Cohen, & Perreault, 2006; Rafols & Meyer, 2010) in sustainability research is not a new revelation (Holling, 2001; Kates, 2016; Komiyama & Takeuchi, 2006; Ostrom, 2009). Given that the challenge faced by sustainability research is one that is multifaceted, many researchers have long advocated for knowledge integration to be supported by new institutions and practices (Bäckstrand, 2003; Jerneck et al., 2011; Koehler & Hecht, 2006; Swart, Raskin, & Robinson, 2004).

Guided by the tenet that the integration of interdisciplinary knowledge is able to address a wider scope of the challenges faced in sustainability research, the current dissertation aims to apply the aforementioned principles of visual perception and cognition to sustainable behaviour interventions. More than just how we perceive disseminated information to enact optimal energy behaviour change, the way we experience the world in general is also largely visual. While a sociopsychological approach to behaviour has been invaluable, there is a lack of studies that have shown due considerations to the neurophysiological characteristics that have been demonstrated in other fields to be of importance (e.g., visual perception, visual information processing). As such, the current work also seeks to demonstrate how the integration of visual perception and cognition principles and insights into sustainability behaviour research is able to not only provide new perspectives to resolving existing issues within the literature but also as a basis for generating potential new intervention strategies to further the sustainability agenda.

To briefly summarize, for the first two studies (Chapter 2 and 3), the work in this thesis aims to address the visual information processing and cognition ‘knowledge gap’ with regards to a conservation intervention context. In particular, the studies will focus on addressing existing assumptions about information acquisition, attention, and visual information perception towards the provision of energy information (e.g., usage feedback information). The aim of these chapters is to provide a sense of how visual parameters could potentially impact

information strategies, via the use of conventional behavioural methodology and neurophysiological approaches (i.e., eye-tracking). For the third study (Chapter 4), a nascent nudge intervention involving the use of visual colour perception and multisensory integration was explored. This study focuses on examining the potential value of applying non-informational visual perception as a potential behaviour change mechanism, as well as highlight the associated biophysiological considerations involved in implementation.

The approaches of the chapters within this thesis are summarized further below:

Chapter 2: Information interventions: Eye-tracking and information perception briefly reviews the literature on information feedback, visual information processing and their impacts on perception and cognition, as well as some context on existing information feedback practices. Following, the review continues with a background on the use of visual neuroscience approaches and the rationale and aims for the current chapter. Experiment design and methodology are introduced, followed by the analysis findings and the discussion of the results. Insights garnered from this chapter is used to guide and justify subsequent experimental design considerations as detailed in Chapter 3.

Chapter 3: Information interventions: Cognition, Perception and Judgement Behaviour examines the existing literature on information interventions, a short discussion of Chapter 2's findings and an introduction on potential cognitive biases, followed by the rationale and aims of the current study. Subsequent text within the chapter details the experimental design, analyses and results, followed by the discussion of the results and a brief introduction of Chapter 4.

Chapter 4: Non-information interventions: Visual colour perception, Thermal perception and Physiology begins the chapter with a brief summary on the background of non-informational interventions, the context of the identified problem, a literature review on multimodal phenomenon, thermal perception and the characteristics of the circadian rhythm. Following, the rationale and aims of the study are discussed, leading on to the experimental design, analyses and results, and lastly a discussion on the findings.

Chapter 5: *Discussion and Conclusions* summarily synthesizes the insights garnered from the empirical findings of Chapter 2 to 4 in the current thesis and discusses the potential limitations, future directions, and implications of the findings.

2 Information Interventions: Eye-tracking and information perception

2.1 Introduction and Literature Review

2.1.1 Information Feedback and Energy Conservation

Of the multiple behavioural interventions employed to help coax energy conservation behaviours, many feature the role of information provision which has not only been used extensively in other fields such as health care (e.g. Kreuter, M., Farrell, D., Olevitch, L., & Brennan, 2000) but is also often the key element of many government energy-efficiency policies. The popularity of information-based intervention strategies has been rapidly growing in the last two decades since the nineties (Nemati & Penn, 2020).

In general, information-based intervention strategies aim to influence decision and behaviour by providing education, reducing information asymmetries and correcting biases, such as learning to associate relevant energy behaviours with outcomes and/or to accurately assess the impact of certain behaviours (Buchanan, Russo, & Anderson, 2014; Delmas et al., 2013). The provision of information effect changes in behaviour by changing perception such as enhancing the availability or accessibility of actions, saliency of existing issue(s), modulating intrinsic factors (e.g., influencing motivation, attitudes, values and/or norms), and/or changing the contextual perspectives in how such issues are viewed (e.g., priming energy conservation to be associated with altruism and trust, environment and health). Consequently, the types of information employed in energy conservation interventions are highly varied, with both pecuniary and non-pecuniary information such as historical consumption, neighbours' and community consumption, price and pricing structure, existing rebate programs, monetary savings due to conservation, providing energy saving tips,

ecological impact of emissions, health impacts of emissions, and pro-social messages (Asensio & Delmas, 2015; Delmas et al., 2013; Ferraro & Miranda, 2013; Nemati & Penn, 2020).

Thus far, the use of information intervention strategies has been suggested to be effective in reducing consumption, with average reductions of 6.24% across a range of 5% and 20% (Darby, 2006; Fischer, 2008; Nemati & Penn, 2020). However, other recent reviews have suggested that the effectiveness of information interventions are much lower, with a more realistic estimate of consumption reductions from monetary, informational and behavioural incentives to be at 1.9–3.9% (Buckley, 2020), or problematically large variations in measured effectiveness ranging from a 55% reduction to a problematic 18.5% increase in consumption (Allcott, 2011; Delmas et al., 2013).

One potential contributing factor may be due to inconsistencies in the implementation of information interventions, even in similar mediums. For instance, feedback information that is delivered to the recipient by mail can vary in how the information is visually and qualitatively represented, such as in numerical, textual, categorical (e.g. happy or sad cartoon faces) (Schultz et al., 2007), or diagrammatical (e.g. bar, pie, or line charts) formats. These differences in information display and communication have been noted in communication studies to have significant impacts on task accuracy, patterns of information utilization, and even interpretation (Sanfey & Hastie, 1998; Shah & Freedman, 2011), such as the direction of information search being slightly more attribute-oriented with information displayed as numbers instead of words (Stone & Schkade, 1991).

Notwithstanding, differences can also arise within informational displays of the same format, such as with significant differences in task performance accuracy as a result of varying the steepness of a graph's slope (Beattie & Jones, 2002). In particular, significant differences in learning and memory was observed to arise even from supposedly 'non-focal' aspects of a visual communication display, such as decorative graphics, (Danielson, Schwartz, &

Lippmann, 2015), indicating a substantial role of information display in influencing individuals' decision processes, i.e., affecting the acquisition of and attention to information, facilitating certain decisional strategies, hindering others, or both (Bettman & Kakkar, 1977; Jarvenpaa, 1989, 1990; Kleinmuntz & Schkade, 1993).

Other previous studies investigating the effects of different information display features (i.e., form, organization, and sequence of information), reported that organization – the structuring of information into patterns (e.g. matrices or lists) – strongly influenced information acquisition, while form (e.g. quantitative/numerical or qualitative/text) strongly influenced information combination and evaluation (Schkade & Kleinmuntz, 1994). Sequence of information was observed to have only a limited effect on information acquisition. Additionally, while all 3 features influenced decision effort exerted, only organization appeared to have an effect on perceived effort (with inconsistencies found between actual and perceived).

While other parameters of information provision (e.g. frequency, duration, clarity, type of information, level of engagement) have received some degree of attention within the extant conservation behaviour literature (Buchanan, Russo, & Anderson, 2015; Chen et al., 2015; Fischer, 2008), there is a severe lack of understanding regarding the impacts of information visual display. Given the potential effects on cognition, perception and behaviour can be quite substantial, the lack of data is concerningly problematic for subsequent intervention planning and design in addition to being a potential impediment in understanding why and how these interventions work.

With regards to existing formats of energy information provision, the utility billing format as recently implemented in Singapore presents an opportune case study for evaluating the effects of information interventions. As one of the most densely populated countries in the world, Singapore is also bereft of indigenous energy and water resources, being reliant on imports and consumption efficiency for the needs of its' population. Thus, sustainability in

both energy and water are key priorities on the national agenda (He & Kua, 2013). In 2016, a significant overhaul, intended to make the information more accessible, was made to the existing format household historical feedback information (i.e. utilities billing information) (EMA, 2016), as part of an initiative to encourage conservation. These changes were thought to allow consumers to clearly perceive their own consumption habits and potentially provision them with an impetus to change their behaviour to be more sustainable.

In particular, consumption information is represented as textual physical units (e.g. *kWH/L*), textual cost information (in *SGD*), as well as in a graphical bar-graph form that conveys multiple information such as historical consumption and social normative and comparative information (i.e., neighbour and national consumption averages) (Figure 3A and B). Such changes, which involve the use of multiple different information types, represent an instance where information interventions are integrated into the regular monthly utilities billing cycle, effectively institutionalizing frequent exposure over a (likely) long-term basis that would theoretically, address intervention durability concerns on households. However, while the changes were publicly explained to be a result of ‘usability’ studies with input from communities, there is scant publicly available empirical evidence to verify its’ effectiveness (or lack thereof).

Notwithstanding, the effects on outcomes such as information acquisition and understanding as a result of different information representations such as graphs is unclear. For instance, while graphs are commonly believed to facilitate comprehension, the processing of graphs relative to text containing the same information may not always be more efficient, being potentially dependent on different factors such as the complexity of the task or the graphs themselves (Kim & Lombardino, 2015).

August 2015 Bill Dated 03 Aug 2015

Account No :
Type :
Deposit :

This is your tax invoice for

SUMMARY OF CHARGES 05 Jul 2015 to 02 Aug 2015		Amount (\$)
Balance B/F from Previous Bill		160.25
Payment on 20-07-2015 - Thank You		-160.25
Outstanding Balance		0.00
Total Current Charges due on 17 Aug 2015 (Mon)		227.29
Total Amount Payable will be deducted from your account with DBS Bank Ltd on 17 Aug 2015		\$227.29

SP Services Ltd
Orchard P.O. Box 341
Singapore 912312
Co. Registration No.: 199504470N
GST Reg No. M2-8920920-4
General Enquiries: 1800 2222333
Credit Arrangement: 6671 7100
Fax: 6304 8229
www.spservices.com.sg
spservices@singaporepower.com.sg

Payment received on or after 02.08.2015 may not be included in this bill.

CURRENT MONTH CHARGES	Usage	Rate (\$)	Amount (\$)	Total (\$)
Electricity Services				
Reading taken on 02-08-2015 : 10371				
Electricity	37 kWh	0.2087	7.73	
	639 kWh	0.2241	143.20	150.93
Gas Services by City Gas Pte Ltd				
Reading taken on 02-08-2015 : 4696				
Gas	76 kWh	0.1762		
	5 kWh	0.1825		14.30
Water Services by Public Utilities Board				
Reading taken on 02-08-2015 : 5278.3				
Water	19.2 Cu M	1.1700	22.46	
Waterborne Fee	19.2 Cu M	0.2803	5.38	
Sanitary Appliance Fee	2 Fittings	2.8037	5.61	33.45
Refuse Removal by Veolia ES Singapore P L				
Refuse	1 Qty	7.00	7.00	7.00
Water Conservation Tax				
	\$22.46	30%	6.74	6.74
Total Charges			212.42	212.42
Goods & Services Tax			14.87	14.87
Subtotal ▶				227.29

For cheque payment :
Crossed cheque is to be made payable to "SP Services Ltd". Please detach and mail this portion with your cheque to Orchard P.O. Box 341, Singapore 912312.
(No receipt will be issued. Please do not send post-dated cheque.)

Payment Due On 17 Aug 2015	Account No	Cheque No	Bank/Branch
Total Amount Payable			\$227.29

41186916593-PS
Page 1 of 3
553-008749-04375

Figure 3A. A sample image of the actual utilities billing information employed in Singapore, prior to revision in 2016.

MR XX
UNIT NO. STREET
SINGAPORE XXXXXX

888 123456-12345

November 2016 Bill

Account No. 1234567890

Total Amount Payable: **\$137.61**

Payment Due: **14 Dec 2016**

This is your tax invoice for
UNIT NO. STREET SINGAPORE XXXXXX

Billing Period
29 Oct 2016 – 29 Nov 2016

Bill Date
30 Nov 2016

Account Type
Domestic

Deposit
\$100.00

Current Charges	Consumption Trend	Total
<p>Electricity Services Usage: 338 kWh</p>	<p>(kwh)</p> <p>Usage: JUN XX, JUL* XX, AUG XX, SEP* XX, OCT XX, NOV* XX</p>	<p>\$64.60</p>
<p>Water Services By Public Utilities Board Usage: 29.51 Cu M</p>	<p>(Cu M)</p> <p>Usage: JUN XX, JUL* XX, AUG XX, SEP* XX, OCT XX, NOV* XX</p> <p>..... Neighbour average — National average *Estimated month</p>	<p>\$63.51</p>

Utilities Saving Tip

Refuse Removal by SembWaste Pte Ltd **\$7.49**

GST **\$9.49**

Current Charges **\$137.61**
(inclusive of GST)

Summary of Charges	
Balance Brought Forward from Previous Bill	\$XXX.XX
Payment on — Thank You	-\$XXX.XX
Outstanding Balance	\$0.00
Current Charges due on 14 Dec 2016 (Wed)	\$137.61
Total Amount Payable	\$137.61

SP Services Ltd: Co. Registration No. (199504470N) T GST Registration No. (M2-8920920-4)

For details on difference between current charges and total amount payable, see Summary of Charges

Payment Due:
14 Dec 2016

Please make full payment by the due date to avoid \$0.50 Pink Notice Fee and 1% Late Payment Charge.

Total Amount Payable:
\$137.61

Account No
1234567890

Cheque No

Bank:
Branch:

8908237103

000000057951

41235678901-/5

Page 1 of 2

888-123456-12345

Figure 3B. A sample image of the revised and updated design of actual utilities billing information employed in Singapore in use since 2016.

2.1.2 Information, Cognition and Behaviour: A Visual Neuroscience Approach

To address the aforementioned visual-information-processing gap within the conservation literature, the current work seeks to characterize the cognitive processes with regards to current/existing formats of feedback information provision (e.g., utilities billing). Traditionally, the challenges of understanding behaviour itself and the inherently metaphysical processes underlying it were tackled by collecting subjective indicators, such as self-reports of attitudes, motivations, knowledge assessments, and other measures that relied heavily on introspection (Baumeister, Vohs, & Funder, 2007). While indispensable as tools for investigating psychological processes such as cognition, perception and attention, such approaches have a set of well-documented limitations, such as being difficult to interpret in some cases, risks of distortion by triggered biases such as social desirability or demand effects, or that individuals themselves may lack the necessary level of introspection needed to provide valid responses and answers (Nisbett & Wilson, 1977a).

Other proximal measures to understand cognitive processes of behaviour such as implicit associations, memory and reaction times are inherently noisy and their validity has been challenged (Arkes & Tetlock, 2004). Conversely, insights using only final choices or judgements are limited in usefulness as they provide little information on the route in which an overt behaviour occurs, such as concerning information acquisition, processing, thinking, and reasoning – aspects which if properly understood, may provide powerful opportunities to elicit change. Thus, the role of cognitive processing and concepts are by large, theoretically and/or conceptually posited and extrapolated, with most socio-psychological studies adopting a classical “black-box approach” – where the processes of the human brain are inscrutable and only to be deduced and/or assumed.

Whereas earlier approaches were limited technically, rapid advances in neurophysiological and psychological measurement techniques within the last couple of

decades have since rendered such issues less relevant for contemporary studies. Instead, progresses in neuroscience and other neurophysiological techniques such as electroencephalography (EEG), positron emission tomography (PET), functional magnetic resonance imaging (fMRI), functional near-infrared spectroscopy, electrocardiogram, galvanic skin responses, and eye-tracking now offer researchers the ability to gain further insights into understanding such processes. Such approaches have also seen applications in areas such as health, ethics, business, (Ballesteros, Kraft, Santana, & Tziraki, 2015; Erickson, Creswell, Verstynen, & Gianaros, 2014; N. Lee, Butler, & Senior, 2010; Nicolaou & Shane, 2014), to examine behavioural phenomena such as preferences, utility and rewards, cooperation, fairness, trust and altruism, learning and strategy (C. F. Camerer, Loewenstein, & Prelec, 2004; C. Camerer, Loewenstein, & Prelec, 2005; Glimcher, Dorris, & Bayer, 2005; McCabe, Houser, Ryan, Smith, & Trouard, 2001; Vercoe & Zak, 2010; Zak, 2008, 2011).

Thus, to address existing challenges in the sustainability behaviour literature, the integration of neurophysiological approaches may help circumvent some of the methodological issues faced with solely relying on traditional measures. One such approach is eye-tracking – a versatile research method to unobtrusively investigate and analyse the underpinnings of continuous free viewing, visual search behaviour and integration processes. In viewing the world and environment around us, our eyes flit from location to location at high frequency, with changes in gaze direction resulting from rapid saccadic eye movements. Useful information is subsequently acquired during periods of relative gaze stability, also known as fixations (Henderson, 2007). The movement of eye direction and fixations are analysed in contemporary eye-tracking approaches to understand the processes involved in identifying and encoding information, effectively providing a means in which data on cues that are utilized unconsciously in reasoning and decision making to be garnered.

Relative to the traditional stimulus-response paradigm in sociopsychological studies, eye tracking is thought to be a comparatively more ecologically valid approach, having been used to study cognitive processes and states, including mind wandering or arousal (Bradley, Miccoli, Escrig, & Lang, 2008; Smilek, Carriere, & Cheyne, 2010), across a range of various disciplines (e.g. learning, communication science, and marketing) (King, Bol, Cummins, & John, 2019; Kok & Jarodzka, 2017; Stickler, Smith, Shi, Caws, & Hamel, 2016; Wedel & Pieters, 2008). In particular, the use of eye-tracking helps reduce reliance on self-report measures and potentially other necessary methodological interruptions of the cognitive and decisional processes of interest. Furthermore, the use of eye-tracking provides a high temporal resolution which allows for the estimation of overall importance and weighting of specific information pieces, as well as enabling the tracking of dynamic processes over time. Relative to other process-tracing techniques such as fMRI or EEG with an equal or even higher resolution, the use of eye-tracking is relatively cheap to acquire and operate (Rahal & Fiedler, 2019).

Fundamental eye-tracking parameters of cognitive processing include gaze coordinates, fixation duration on area(s) of interest (AOIs), as well as the number of fixations on each AOI (Cook & Wei, 2017; Cook, Wei, & Preziosi, 2017; Holmqvist et al., 2011). Fixation duration, quantified typically as the eye movement pattern on an explicit spatial location at a temporal threshold of roughly 100 to 200 *ms* (Manor & Gordon, 2003), is one of the most common and informative eye movement measures employed, having been observed to increase under increased processing load (i.e. duration increases when processing becomes more effortful under free viewing conditions) (Meghanathan, van Leeuwen, & Nikolaev, 2015). The use of eye tracking as an indicator of cognitive effort is based on the immediacy assumption that proposes that the fixation of the eyes on text during reading necessitates the immediate engagement of mental processing (of the text) (Just & Carpenter, 1980). Thus, an increase in

both fixation duration and count reflects a similar increase in mental processing. Studies have also indicated an overlap between processes involved in working memory and processes involved in visual search (Han & Kim, 2004), such that working memory task demands may hamper central executive functioning from contributing towards visual search, resulting in interference and longer fixation durations (Peterson, Beck, & Wong, 2008). In general, working memory and attention are intimately related, potentially sharing the same resource limitations, and are theorized to play roles in guiding perceptual selective attention and processing (e.g. Kiyonaga & Egner, 2013). Additionally, it is observed that fixation duration is sensitive to the amount of attention deployed to a fixated location (Henderson, 2007), and that memory load lengthens the average duration of fixation (McCarley et al., 2006). Thus, the total fixation time is hypothesized to induce cognitive processing, serving as a measure of cognitive performance and load (Mayer, 2010).

With regards to sustainable behaviour research, the use of eye-tracking approaches can be implemented to address a multitude of research questions. In particular, to illuminate the information search, acquisition, and integration processes of behavioural interventions employing informational provision strategies. To date, there have been only a few studies that have integrated eye-tracking into their investigations; such as the use of eye-tracking monitoring in a study to investigate the effects of the EU energy label on information processing and (purchase) decision making (Waechter, Sütterlin, & Siegrist, 2015). The findings revealed that energy labels generally triggered attention towards energy information; however, it was also noted that the current visual information presentation format of these labels did not facilitate the integration of energy-related information in viewers, such that consumers were so focused on energy-efficiency, that it led to an undesired effect of disregarding information on actual energy consumption. This potentially could lead to increases in total energy consumption, as an appliance's excellent ratings on energy efficiency

does not automatically imply little consumption; thus, consumers may inadvertently choose an energy efficient but higher capacity appliance, leading to an overall increase in absolute energy consumption instead (Waechter et al., 2015).

In conjunction with behavioural choice data, the use of eye-tracking data allows for evaluations of information search behaviour and information perception that would allow researchers to uncover unwanted effects, such as potential information misperception arising from various design attributes of informational provision. For instance, the use of eye-tracking in previous studies of graph understanding with regards to kinematics was able to observe correlations between judgements of confidence in understanding and answering questions with differences in visit durations (Klein et al., 2020). Other studies regarding gaze behaviour and behavioural outcomes such as piloting performance have shown that optimal gaze behaviour is associated with improved flying performance under both normal conditions and under stress (Ziv, 2016). Other studies focusing upon consumer purchases decisions have also shown to be able to link psychological constructs with viewing behaviour and behavioural outcomes, such as in one other study which reported that individuals whom scored high on the buying impulsiveness scale (BIS) tended to fixate less on in-store signs and more on displays, relative to individuals who scored low on the BIS. Moreover, visual attention to informational signs was also reported to positively impact the purchasing behaviour of high BIS participants, while visual attention to displays did not (Khachatryan et al., 2018). Conversely, applications to energy usage behavioural studies are scarce, with most studies relying instead on other end-measures, such as changes in overall consumption or self-reported measures of willingness to take action.

With eye-tracking, outstanding questions within the literature regarding methodological differences, i.e., those pertaining to the type(s) of display medium, visual configuration of information, and other informational and visual display attributes, can be

thoroughly investigated, such as in real-world cases of feedback informational provisioning. With recent empirical evidence suggesting both low-level visual features and social information to have an influence on gaze behaviour (Rubo & Gamer, 2018), the use of eye-tracking could be used in such instances to determine if such information provisioning tactics exhibit congruent effects. In summary, the use of eye-tracking may be used to address such gaps within the literature, given that the use of recent developments in neurophysiological approaches is able to not only circumvent the limitations of existing sociopsychological approaches but also provide tools to evaluate actual real-world implementations of information behavioural interventions.

2.1.3 Rationale and Aims

The aims of this study are to characterize the gaze behaviour involved in information acquisition with regards to feedback information, as is typically provided in a typical household utilities bill in Singapore. The recently updated domestic utilities billing format in Singapore, as aforementioned in the previous sections above, was adopted as a stimuli template for this study due to its' high ecological validity, and the use of multiple information types and intervention strategies (see Figure 3B). As part of an initiative to encourage conservation, changes to the manner consumption information are represented were implemented with the aim to allow consumers to clearly perceive their own consumption habits and potentially provision them with an impetus to change their behaviour to be more sustainable. In particular, consumption information of a utility type is given textual physical units (e.g., *kWH/L*), textual cost information (in *SGD*), as well as in a graphical bar-graph form conveying both historical consumption and social comparative information (neighbour and national averages). Employing eye-tracking methodology, this study attempts to characterize gaze behaviour on the different information forms provided, in the context of a cognitive judgement-making task based on subjective evaluations of 'efficiency'.

For the aforementioned stimuli, the inherent computational differences (i.e., ease of acquisition) between the varying visual forms of information are posited to impact upon cognitive and attentional processing, potentially resulting in significant differences in gaze behaviour to each AOI denoting the visuospatial locations of each information form. In particular, the graphical representations of consumption information are noted to contain more information, relative to the other existing textual physical consumption units, or textual cost information types. In addition to presenting consumption information for the single relevant month, graphical representations of consumption information within the actual utility billings and the current employed stimuli also includes the social comparative/normative information of a hypothetical household's peers and the household's historical consumption information of up to five previous months.

As such, it is expected that the gaze metrics for graphical consumption information would reflect higher processing loads and attentional salience – being significantly higher than the other informational items on the utility bill stimuli. To investigate gaze characteristics of individual information items (i.e., AOIs) on the utility billing stimuli, comparisons between intra-informational items were subsequently examined. Thus, to guide the current study's investigations, the following hypotheses were formulated for testing:

- *H1.1*: The fixation duration of other information elements' AOIs (i.e., textual physical units, textual cost units for individual utilities, or textual cost units for total cost) is expected to be lower than the fixation duration of AOIs associated with both graphical information items.
- *H1.2*: The fixation count of other information elements' AOIs (i.e., textual physical units, textual cost units for individual utilities, or textual cost units for total cost) is expected to be lower than the fixation count of AOIs associated with both graphical information items.

Lastly, information and visual representations of different levels of utility consumption may potentially impact cognition and perception and attentional salience, resulting in observable differences to subjects' viewing behaviour. For instance, low-level visual features such as the size of 'bars' in a graphical depiction of consumption information may potentially impact viewing behaviour by virtue of increased saliency, or when high and low consumption levels are contrasted with average consumption levels. Other phenomenon such as the potential socially negative or positive valence(s) associated with social-normative comparisons of consumption, (e.g., via present information of peer averages on utility consumption) may also influence cognitive processing and impact participants' viewing behaviour. To investigate, the following predictions were formulated:

- *H2.1*: For the graphical elements, fixation duration is predicted to be higher for bar heights associated with higher utility consumption in this context, and lower for bar heights associated with lower utility consumption, relative to fixation durations of bars with average height associated with average utility consumption.
- *H2.2*: For the graphical elements, the fixation count is predicted to be higher for bar heights associated with higher utility consumption in this context, and lower for bar heights associated with lower utility consumption, relative to fixation durations of bars with average height associated with average utility consumption.

2.2 Design and Methodology

2.2.1 Participants

A total of 14 participants (5 females; $M_{\text{age}} = 25$; $SD_{\text{age}} = 2.66$) were recruited through online channels for the current study. All participants had reported normal or corrected-to-normal vision with no history of visual impairments or diseases. Of the fourteen participants,

one participant was omitted from the analyses due to technical issues with recording. The study was approved by the Nanyang Technological University Institutional Review Board and all procedures were performed according to guidelines.

Power analysis was conducted using the power analysis calculator from (Judd, Westfall, & Kenny, 2017), with an estimated effect size of approximately 1.0276 (Coral, 2016), variance partitioning coefficients based on the model examining two-way interactions between fixed effects variables, and an expected power of 0.8. The minimum number of participants needed to power the study is 7.2. Reversing the analysis of the results using the same model, the power of the current study is 0.929 which is above the recommended level of 0.8 (Brysbaert, 2019; Judd et al., 2017).

2.2.2 Materials and Apparatus

Eye tracking measurements were obtained using a monitor display eye-tracker (*Tobii T120*) (Morgante, Zolfaghari, & Johnson, 2012). The stimuli were presented on the 11" *TFT* monitor at a display resolution of 1280 by 1024. The eye-tracker was connected to a desktop computer (*HP ProDesk 600G1 TWR* with an *Intel® Core™ i7-4770 CPU at 3.40 GHz* processor, *AMD Radeon™ HD8490* and *Intel® HD Graphics 4600* GPUs, with 8 GB of ram, on a 64-bit Windows 7 Enterprise Operating System. The computer was used to run *Tobii Studio™* (v 3.3.2) software for recording of eye parameters and designating areas of interests (AOIs). Stimuli presentation and behavioural responses were conducted using the online service *Qualtrics™* deployed within the *Tobii Studio™* software environment. Behavioural responses were inputted using a desktop mouse and keyboard connected to the desktop computer, and viewing distance was kept at approximately 70 cm across all participants.

2.2.3 Stimuli

The experimental stimuli consist of a hypothetical households' utilities bill – modelled after the actual billing format, currently in use by the Singapore utilities company (*SP services*)

since 2016 (EMA, 2016). The stimuli employed were as described in the sections above (see Figure 3B), with each bill containing a hypothetical household's consumption information of both water and electricity utility type for that current month. Within each bill, the consumption information of each individual utility is presented in textual form as both pecuniary cost (in *SGD*) and physical units (*kWH/L*), while graphical representations (i.e., bar charts) of each utilities' consumption information showed monthly consumption trends for a historical period of up to previous 6 months.

In each of the aforementioned bar graphs, the total utility usage of each individual month is represented as a separate bar along the horizontal 'x' axis. Each graph also features a solid and dotted horizontal line to represent (hypothetical) calculated national and neighbourhood averages respectively, although for experimental design purposes, both (national and neighbourhood) averages were depicted to be equal to each other across all experimental conditions and levels. The consumption levels of either utility type (electricity and water) were dictated at either of three pre-defined levels: low, average and high – representing 50% lower (low), equal (average), or 50% higher (high) utility consumption relative to the national/neighbourhood averages, respectively. As such, the current study employed a 3 (consumption level: low, average, high) by 2 (utility type: electricity x water) within-subjects design.

2.2.4 Procedure

Upon arrival at the laboratory, each participant was briefed on the experiment and asked to sign a consent form. Participants were then asked to sit in an upright chair in a quiet testing room with artificial LED ceiling lighting. Participants were instructed to minimize body movements, as well as to keep their gaze directed towards the screen during the experimental tasks. A calibration procedure was conducted prior to starting the experiment by an experimenter, who was also present to answer any questions or concerns (see Figure 4).

Participants were subsequently given a general introduction of the study and the experimental task instructions on-screen before undergoing a training phase where they attempt a set of 4 test trials alone. Following, participants were presented with the task instructions once more on-screen before the actual experimental trials. In between each experimental phase, participants were offered to take a break if needed.

Figure 4. Experimental procedure sequence of events.

For both the training and actual trials, each trial started with a fixation cross (black cross against a white background) for a brief duration of 1000 *ms*, followed by the experimental stimuli, and subsequently a set of 3 task questions where participants were asked to rate the efficiency of the household on 3 aspects: overall, electricity and water. Responses were all recorded on an on-screen numeric slider scale (i.e., 0 = highly inefficient, 50 = average, and 100 = highly efficient) (see *appendix C*). Each question appeared on a separate page in randomized order with no time limit imposed (see Figure 5). The order of stimuli presentation was randomized and the time of exposure for each stimulus was set at 10 seconds. No restrictions on timing were given for participants to respond to each of the 3 task questions.

Figure 5. Sequence of presentation and events in each trial.

2.2.5 Data Analysis

Fixation, defined as the time an individual's gaze remained fixated within the boundaries of a particular AOI while taking into account the number of attentional shifts, was distinguished and coded from other gaze events (e.g. saccades) using the *Tobii Fixation* filter – a velocity-based algorithm within the *Tobii Studio*TM software (v 3.3.2) with a peak velocity threshold of 40°/s (A. Olsen, 2012). A minimum fixation duration of 100 ms, a commonly employed threshold, was employed (Manor & Gordon, 2003).

*Tobii Studio*TM software was used to define AOIs used in the experiment, with the boundaries of each AOI corresponding to each different informational text and graphical item found within the utility bill stimuli. Overall, a total of 11 AOI were defined for the following information items on the bill (see Figure 6): for each utility's bar graphs (AOI 2 labelled for electricity and AOI 3 for water), for each utility's textual physical units consumption information (AOI 4 for electricity and AOI 5 for water), for the textual cost of each utility's

usage (AOI 7 for electricity AOI 8 for water), and lastly for the textual total cost information (i.e. the summative cost of all individual items including tax), distinguished accordingly in order of their spatial locations on the bill. In particular, AOI 6 was used to label for total cost information in the top right-hand corner, AOI 9 for total cost information located in the middle right upper section, AOI 10 for middle lower, and AOI 11 for total cost information located at the bottom right-hand corner. One additional AOI (AOI 1) was used to label the location of the fixation cross, shown in-between stimuli exposure, for experimental control purposes.

Figure 6. Demarcation of various AOIs employed in the current study. Base stimuli are as seen in Figure 3B. See *appendix A* for more information on each AOIs' gaze metrics.

The choice of analysis in the current study involved a series of linear mixed-effects model (LMM) analyses, with a Maximum Likelihood estimation method using the *R* statistical software and '*lme4*' (Bates, Mächler, Bolker, & Walker, 2015). The LMM analysis was

selected for its flexibility in allowing a wide variety of correlation patterns to be explicitly modelled, even with correlated data and unequal variances. Evaluation of the significance of effects in the models involved the use of Satterthwaite's method ANOVA through the '*lmerTest*' statistical package (Giesbrecht & Burns, 1985; Hrong-Tai Fai & Cornelius, 1996; Kuznetsova, Brockhoff, & Christensen, 2017), while model effect size estimates and post-hoc contrasts were obtained via the "*MuMIn*" statistical package and '*emmeans*' statistical package with Tukey's adjustments (Lenth, 2019).

For both measures of fixation duration and count, the current study employed AOIs, as well as the visual information of consumption levels of each utility ('electricity/water') as potential fixed effect variables. For all models, individual participants were modelled as random effects. Model structure was evaluated by conducting incremental nested model comparisons (e.g., null models against reduced models, and against full models).

2.3 Results

For fixation duration, an LMM structure with the fixed effect variables 'AOI' and a 2-way interaction between the two fixed effect variables 'electricity' and 'water' consumption information (conditional $R^2 = .30$) was found to significantly improve on model fit indices over a null (no effects) ($\chi^2 = 152.86$, $df = 13$, $p < .001$) and a reduced model (no interaction present) ($\chi^2 = 4.09$, $df = 1$, $p = .043$). From the results of the LMM analyses, a significant main effect of AOI ($F_{10, 459.3} = 17.5726$, $p < .001$), as well as a significant 2-way interaction effect between electricity and water consumption information ($F_{1, 455.49} = 4.1759$, $p = .042$) was observed, indicating a significant role of information type on fixation duration.

Subsequent post-hoc analyses indicate the utilities consumption graphs for both electricity and water to have the highest fixation durations, relative to other AOIs (Figure 7), in-line with predictions in hypothesis *H1.1*. In a series of pairwise comparisons with Tukey's

adjustment, mean fixation duration on AOI 2 (electricity graph) was observed to be significantly higher than all other AOIs except for AOI 6 (total cost 1) ($t_{479} = 2.772, p = .172$), AOI 7 (electricity cost info) ($t_{472} = 2.904, p = .125$) and AOI 11 (total cost 4) ($t_{474} = 3.06, p = .083$), indicating partial support for *H1.1*. As predicted in *H1.1*, the mean fixation duration on AOI 3 (water graph), was also observed to be significantly higher than all other AOIs. Mean fixation duration for AOI 3 was also observed to be significantly higher including AOI 2 (electricity graph) ($t_{469} = -4.821, p < .001$). Pairwise contrasts of mean fixation duration between the three different bar heights denoting the levels of utility consumption (i.e., high, average and low), revealed no significant differences, in contrast to predictions made in *H2.1*.

Figure 7. Boxplot of Fixation Duration (*ms*) means (y-axis) across each different AOI (x-axis).

For fixation count, an LMM structure with the fixed effect variables ‘AOI’, ‘Electricity’ and ‘Water’ consumption information (conditional $R^2 = .40$) improved the model fit indices significantly over the null model (no fixed effects) ($\chi^2 = 234.69, df = 12, p < .001$). No significant improvements in model fit were observed for comparisons with more complex models (e.g., 2-way interactions). From the results of the LMM analyses, AOI was revealed to have a significant main effect ($F_{10, 460.4} = 30.31, p < .001$), indicating a significant role of information type on fixation count (Figure 8). Similar to fixation duration, subsequent post-

hoc comparisons with Tukey's adjustments indicate both AOIs 2 and 3 (electricity and water graphs respectively) to have significantly higher fixation count means relative to all other AOIs, in-line with predictions made in *H1.2*. AOI 3 was also revealed to have a significantly higher fixation count relative to AOI 2 ($t_{470} = -6.389$, $p < .001$). Across the three different bar heights representing low, average and high levels of utility consumption information, pairwise comparisons of fixation count revealed no significant differences, in contrast to predictions for *H2.2*.

Figure 8. Boxplot of Fixation Count means (y-axis) for each AOI (x-axis).

2.4 Discussion

To recap, the aims of this experiment were to investigate and characterize the gaze behaviour of participants in response to the presentation of information on energy consumption. For this study, it is predicted in *H1.1* and *H1.2* that there would be differences in fixation duration and count (respectively) between the different forms of consumption information (e.g., graphical, textual cost and physical units) found within the current utilities billing format, such that graphical representations of utility consumption within this context were expected to have relatively higher fixation durations and counts. Lastly, different bar graph heights representing the respective consumption levels of either utility type (e.g., low, average, high) were predicted to differ in both fixation duration (*H2.1*) and count (*H2.2*), such that bar heights representing high consumption levels were associated with higher fixation duration and count than bar heights representing average consumption levels, while bar heights representing low consumption levels were associated with lower fixation duration and count than average consumption levels.

In line with the predictions in *H1.1* and *H1.2*, results of statistical analyses revealed a main effect of AOI for both measures of fixation duration and fixation count, suggesting the form of information to potentially play a significant role in attention, with regards to visual information provision strategies. In particular, fixations on the graphical representation of consumption information were observed to be the highest in both frequency and duration, relative to other information regarding utility consumption, such as textual total cost, textual breakdown cost (per utility), or consumption in textual, physical units. While only partial support for *H1.1* was found – such that mean fixation durations for electricity graph information did not differ against several textual cost information items, water graph information, in contrast, was observed to differ in fixation duration from all other textual information types, in-line with predictions. Similarly, analyses of fixation counts indicated

support for hypothesis *H1.2*, with significantly higher fixation counts relative to all other textual information types. As mentioned prior, a potential reason for our observations could be attributed to unequal computational equivalence of the different information items; in particular, higher attentional salience is accorded to the graphical forms of consumption information, which, simultaneously, included multiple types of information regarding consumption that are not present within the other textual items, for instance social normative information for comparisons (e.g., peer averages), historical comparisons (e.g., 6 months) compared to the other textual items which only provided information regarding the latest (relevant) month.

While only fixation duration appeared to have a significant 2-way interaction effect, there were no statistically significant differences across various pairwise comparisons. These differences in both fixation duration and count suggest a potentially high level of importance of graphical representations of information on attention, indicating that the information in both graphs was highly relevant to the task of making efficiency judgements, and/or potentially that the information was more difficult to extract and process (e.g., interpretation of information was more ambiguous). If true, the potential ambiguity or cognitive load explanation, for extended gaze viewing durations and higher fixation counts towards graphical depictions of utility usage, should not be reflected in between-utility comparisons (e.g., gaze metrics between electricity and water consumption graphs).

The current findings also revealed significant differences in both gaze parameters between similar graphical representations of either utility type's consumption levels; in particular, both fixation duration and fixation count measures were significantly higher for water consumption graph, as compared to electricity consumption graph. These findings suggest that the differences in gaze behaviour were unlikely to be due to higher processing load, as both types of informational elements (i.e., graphical representation) were similar;

rather, it is possible that the differences are due to higher perceived relevance, and/or attentional salience. Potentially, the results suggest that the subjective perception of the two utilities to be different, although the reasons for this are currently still unclear. One potential mechanism for such differences in subjective perception between utilities may involve ontological differences, such as the degree of semantic relatedness.

To investigate this, additional post-hoc investigations using the WordNet® database (Miller, 1995) via the WS4J WordNet Similarity tool (<https://ws4jdemo.appspot.com/>) (see *appendix B*). The Princeton WordNet®, a free and publicly available lexical database of the English language (Miller, 1995) was used as the data-source for semantic relatedness in the current dissertation. WordNet links words into semantic relations including synonyms, hyponyms and meronyms, and have been widely used in the literature, with numerous uses involving but not limited to lexical semantics, computational linguistics and natural language processing, as well as in constructing various corpora for other languages (i.e., the Global WordNet Association). In our subsequent analyses, the term “water” was observed to potentially be more semantically related to the concept of “efficiency”, relative to “electricity” (Banerjee & Pedersen, 2002; Hirst & St-Onge, 1998; Jiang & Conrath, 1997; Leacock & Chodorow, 1998; Lin, 1998; Resnik, 1995; Wu & Palmer, 1994). Thus, it is plausible, that pre-existing idiosyncrasies such as differences in association strength might have played a role in driving the observed differences in gaze parameters between either utility’s graph.

Regardless, more investigations are required to verify the potential causes, due to the potential implications on current and future behavioural interventions. For instance, should semantic relatedness drive differences in perceptions of either utility (e.g., perceptions of efficiency), the design of utilities billing information may have to pay greater considerations to the terminology used, potentially displaying terms that could help trigger increased attention towards efficiency, and sustainability information and behaviours.

Lastly, in contrast to predictions made in hypotheses *H2.1* and *H2.2*, no significant effect of bar sizes representing consumption levels for both measures of fixation (i.e., duration and count) were observed, suggesting an information perception equivalence despite the observed differences in low-level visual features such as bar sizes. While the current results appear to suggest the absence of potential influence from low-level visual features, such as visual contrast arising from differences in size/height, it is unclear as to whether the lack of differences might have stemmed from manipulation issues, such as low personal relevance. To further expand, as the context of the study featured a hypothetical household, potentially this may have also resulted in low affective valence to be associated with different consumption levels, relative to socio-normative comparisons, inadvertently leading to minimal impact on resulting cognition, visual perception and observable gaze behaviour.

In conclusion, the findings of the current study have revealed a significant effect of informational forms on attention. In particular, graphical depictions of consumption information appeared to be more attentionally salient, than textual representations of either physical units of consumption or cost information. Moreover, the results also revealed a significant difference in visual gaze behaviour between electricity and water utility information, suggesting either the influence of low-level visual features, such as spatial position, or inherent qualitative differences in semantic properties to have a significant influence on cognition, perception and attention.

While eye-tracking analysis can provide critical insights into how information is attended to, cognitive processes cannot be directly inferred from eye-tracking data alone (Kok & Jarodzka, 2017), for instance, revealing whether a comprehension difficulty reflected in eye movements actually leads to a comprehension failure or success, what an individual is actually thinking, or why an individual looked at a certain element. Thus, triangulation with other methods (e.g., think-aloud or behavioural responses) as well as with theory is necessary to

effectively use eye-tracking in studying perceptual and cognitive processes. It is also critical to conduct subsequent experiments in a similar paradigm to determine if the aforementioned observations are translatable into actual cognitive and behavioural outcomes (i.e., decision making and judgement). For example, whether the assessment of consumption within either utility is accurate for individual sections (e.g., utilities), how information regarding both utilities may interact with each other, and whether the observed characterization of visual information search behaviour and inferred cognitive load in the current study is reflective on actual observed task performance. To this end, the subsequent study attempts to investigate behavioural responses in individuals, accounting for sufficient statistical power, while being less costly and having less interference and restrictions (i.e., absence of calibration and head movement restrictions may help reduce any potential existing awareness of an eye-tracker) to perform. To complement and further investigate the current findings regarding informational feedback strategies, the second study involving behavioural cognitive judgements is conducted within a similar visual information context to allow for comparisons and inferences across similar visual parameters to be drawn.

3 Information Interventions: Cognition, Perception and Judgement behaviour

3.1 Introduction and Literature Review

3.1.1 Information strategies: A recap and literature review

Of the plethora of different behavioural interventions employed within the literature, many feature the role of information provision, which has not only been used extensively in other fields such as health care (e.g. Kreuter, M., Farrell, D., Olevitch, L., & Brennan, 2000) but is also often the key element of many government energy-efficiency policies. While the essence of information intervention strategies is to clearly communicate specific knowledge or information, there are also many different information communication parameters involved that can influence intervention effectiveness. For instance, within the literature exists a wide variety of mediums used, e.g. workshops (Geller, 1981), mass media campaigns (Hutton & McNeill, 1981; Luyben, 1982; Staats, Wit, & Midden, 1996), home audits (tailored info). However, despite each of these different mediums possessing many inherently different properties (e.g., saliency, ease of extraction/comprehensibility) that are highly impactful on the resulting effectiveness of an intervention (e.g., information extraction outcomes), the impact of such properties has received little to no focus within the sustainable energy behaviour literature.

Notwithstanding, differences can also exist even between information provision interventions employing similar mediums: for instance, feedback information intervention, that is delivered to the recipient via mail, can vary in how the information is presented visually and qualitatively, such as in numerical, textual, categorical (e.g. happy or sad cartoon faces) (Schultz et al., 2007), or diagrammatical (e.g. bar, pie, or line charts) formats. Following an old argument by cognitive scientists, that information visual displays of informational

equivalence are not necessarily computationally equivalent (Larkin & Simon, 1987), problematically, such differences and their potential impact on outcomes, such as information uptake, accuracy of perceived information, and even the influence on the effectiveness on the intervention success, are rarely discussed.

For instance, in a study which presented the same information to participants in eight distinct forms (i.e. a numerical table, two types of text forms, and five different types of bar graphs), it was revealed that each of the different formats yielded varying levels of accuracy and patterns of information utilization (Sanfey & Hastie, 1998). Similarly, distinct interpretational differences were reported by viewers in one instance, when the same information was presented in either a line or bar graph format (Shah & Freedman, 2011) (Figure 9). In particular, the same information represented in a bar graph (top chart) was reportedly more likely to elicit descriptions of main effects and “ $z - y$ ” (i.e., variable in the legend) interactions, than in a line graph (bottom-chart) which was more likely to elicit descriptions of “ $x - y$ ” interactions.

In another study, where the authors specifically sought to demonstrate the computational inequivalence of two informationally equivalent Cartesian graphs, it was observed that computational advantages were able to outweigh factors such as user familiarity (Peebles & Cheng, 2003). Notwithstanding, differences can also arise within informational displays of the same format, with findings of significant differences in task performance accuracy as a result of varying the steepness of a graph’s slope (Beattie & Jones, 2002).

Communication research has also produced evidence, indicating that supposedly ‘non-focal’ aspects of a visual communication display, such as decorative graphics, have a significant, positive impact on different cognitive and attentional aspects, such as learning and memory despite initially appearing to be detrimental to learning acutely after exposure (Danielson et al., 2015). With regards to energy conservation behaviour, this problematic lack

of consideration for such factors may ultimately result in not just reduced intervention effectiveness, but negate any potential reductions via unwittingly triggering other undesirable backlash effects (i.e., rebound effects). For example, the findings of an evaluative study, on the EU energy label, revealed that despite being effective at triggering consumers' attention towards energy information, the existing presentation format of visual information ultimately led to the perception of information to be distorted (i.e. subjects were found to have focused more on energy efficiency grade while disregarding actual consumption of an appliance which may be higher than less efficient appliances) (Waechter et al., 2015).

Figure 9. A sample stimulus item adapted from Shah & Freedman (2011), where the same information is represented differently in two different graphs: (Top) a bar chart with different heights and shading; (Bottom) a line graph with different line styles (e.g., dashes, solid or dotted) and simple shapes (e.g., squares, circles and triangles).

Using information labels (i.e. appliance energy efficiency labels, see Figure 10) to guide optimal consumer appliance purchase behaviours, research findings have indicated that ‘more’ informative labels – of which may include the range of operating cost information, e.g. for lifetime and annual cycles, categorical efficiency grade in either text, diagram and/or colour-codes, comparative information, e.g. relative to other similar class appliance options, or energy efficiency endorsements by different organizations/authorities – to be effective in encouraging efficient purchases, relative to ‘simpler’ energy efficiency labels. Specifically, it was reported that appliance labels with more information pertaining to an appliance’s energy efficiency, relative to labels with less information, had a substantial impact in encouraging higher energy efficiency choices, although it was also noted that there was some distortion in perception, resulting in undervaluation of operational cost savings, and subsequently, energy efficiency (Newell & Siikamäki, 2014).

Similarly, other studies on energy efficiency labels report good consumer awareness of such labels; that consumers were likely to be more attentive or even pay more for such endorsements (Junyi Shen & Saijo, 2009), although the incentive to pay more was also reported to be influenced by frequency of appliance use, suggesting the influence of other variables such as perceived optimality of cost/savings. Other findings on the impacts of the labelling design in Europe have suggested that comparative categorical labels are more effective than other designs (e.g. the Energy Star label: an energy efficiency label that consists only of a logo which communicates the product’s endorsement by the US EPA agency), in communicating energy performance and efficiency concepts to consumers (Molenbroek et al., 2014).

Figure 10. Energy efficiency labels with variations in amount of information i.e. more or less informative, across four information type categories (adapted from Newell & Siikamäki, 2014). (1) Current EnergyGuide label with full information (estimated yearly operation cost, energy use, range of yearly operation cost of similar appliances). (2) Variant with yearly operation cost and range of cost of similar appliances only. (3) Variant with yearly energy use only. (4) Variant of B with no logo or colours. (5) Variant with only estimated yearly operation cost, with no logo or colours. (6) Variant of 2 with Energy Star label. (7) Variant of 4 with Energy Star label. (8) Energy Star label only. (9) Variant of 1 with CO₂ information expressed similarly to that of yearly energy usage (numeric data). (10) Variant of 4 with CO₂ information expressed as graphics and numeric data. (11) CO₂ graphic and numeric data only. (12) EU-style efficiency grade label with operating cost.

These variations in visual parameters and information representation, when compounded with differences in other information provision attributes, such as frequency, duration, clarity, the type of information and level of engagement, could have also contributed to the observed inconsistencies in intervention effectiveness (Buchanan et al., 2015; Chen et al., 2015; Fischer, 2008), given the lack of rigorous evaluative studies that are, in part, due to the high practical difficulty and cost. Thus, it is highly important that research examining why and how interventions work is conducted.

With regards to the findings from Study 1 (Chapter 2), it was noted that feedback information provision strategies such as those incorporated into existing real-world usage (i.e., utilities billing in Singapore) may have certain idiosyncratic effects on information perception, cognition and attention, based on the current visual formatting of the various information elements. In particular, differences in viewing behaviour in the context of a judgement task of utilities efficiency was observed to be biased towards more complex information elements such as graphical representations of consumption history, relative to other elements (e.g., text representations of pecuniary and physical consumption of the respective utilities). While requiring more empirical testing to confirm, the preliminary results of the study to characterize gaze behaviour on stimuli consisting of mock-ups of existing utilities bills in Singapore suggest the presence of potential differences in the subjective perceptions of different utility types (i.e., electricity, water), in which the mechanisms are unclear, suggesting careful placement of either utility's information to be arranged.

Moreover, beyond the potential visual information perception effects of aesthetic parameters, the provision of multiple utilities in feedback information as demonstrated in the existing utilities billing format distributed to households in Singapore may pose other issues via the engagement of non-conscious socio-psychological mechanisms. For instance, the moral licensing effect (also known as self-licensing, moral self-licensing, moral licensing, or

licensing effect) – the subconscious phenomenon where virtuous behaviour in one domain may free people to engage in less moral behaviour in other domains (Effron & Conway, 2015) could occur from perceiving savings in one utility to ‘offset’ usage in another. The licensing effect has been identified to be a potential factor of rebound effects in the energy conservation literature: less-than-anticipated reductions towards improvements in energy efficiency as a result of negative spill-over effects (Greening, Greene, & Difiglio, 2000; Sorrell, 2007; Tiefenbeck, Staake, Roth, & Sachs, 2013). Critically, the magnitude of rebound effects can be quite substantial (i.e., ranging between 40 and 70% for transport), although varying across the different categories (e.g., 2 to 60% for domestic space heating, 10 to 40% for water heating, or 5 to 12% for residential lighting) (Azevedo, 2014; Frondel, Flores, & Vance, 2017; Frondel, Peters, & Vance, 2008; Frondel, Ritter, & Vance, 2012; Frondel & Vance, 2013, 2018; Greening et al., 2000).

Different competing socio-psychological theories have been proposed to underpin moral licensing. For instance, licensing effects are thought to occur because of moral identity; that as individuals differ in the degree to which they are connected to an issue, lower levels of moral aspiration for individuals who are relatively less connected results in faster disengagement from ‘moral’ behaviours, relative to those whom are more deeply committed to an issue (Sachdeva, Iliev, & Medin, 2009). Two other models proposed include the moral credits model (where metaphorical moral credits from good deeds balance out bad ones) and the moral credential model (that good deeds reframe bad deeds; where initial behaviour serves as a lens through which subsequent behaviour is interpreted) (Merritt, Effron, & Monin, 2010; D. T. Miller & Effron, 2010; Monin & Miller, 2001).

Other potential effects that may influence perception includes the anchoring effect (anchoring bias), a robust cognitive phenomenon where decision makers are disproportionately influenced to bias judgements towards an initially presented parameter (Furnham & Boo, 2011;

Oppenheimer, LeBoeuf, & Brewer, 2008; Thorsteinson, Breier, Atwell, Hamilton, & Privette, 2008; Tversky & Kahneman, 1974). For instance, the perception of consumption in one utility may subsequently result in distortion of consumption judgements for the other utility. Regarding the underpinnings of the effect, different models of anchoring exist, with early explanations of anchoring effects proposing an anchoring-and-adjustment heuristic, where insufficient adjustments on an initially presented parameter yield estimates that are biased towards the anchor values (Tversky & Kahneman, 1974). Subsequently, the selective accessibility model derived from confirmatory hypothesis testing theory suggests anchoring effects to result from activation of information consistent with the anchor parameters; that the anchor value is assumed to be evaluated as a plausible answer, influencing subsequent answers to be of values consistent with the anchor (Mussweiler & Strack, 1999; Strack & Mussweiler, 1997; Wegener, Petty, Blankenship, & Detweiler-Bedell, 2010). More recently, an attitude change theory of anchoring effects is proposed; that the exposure to an anchor influences attitudes to be more favourable to the attributes of the anchor, thus biasing subsequent responses to be similar (Blankenship, Wegener, Petty, Detweiler-Bedell, & Macy, 2008; Wegener et al., 2010).

Another potential heuristic that may influence information perception is the halo effect – a cognitive bias whereby people form an opinion regarding the characteristic of an attribute of an entity (e.g., an object, person or concept) based on their predisposition (negative or positive) towards another attribute (Thorndike, 1920). For instance, due to the stronger association with the concept of efficiency, evaluations of ‘water’ utility consumption may be judged more favourably, relatively to similar representations of consumption of electricity, resulting in a distortion in how information is perceived. As such, the water consumption behaviour of an individual may be adversely influenced (higher consumption), resulting in negative consequences in the context of conservation (the reverse halo effect). While typically

applied onto people (Nisbett & Wilson, 1977b; Timothy Coombs & Holladay, 2006), many marketing studies have since applied the halo effect onto other categories including brands (Leuthesser, Kohli, & Harich, 1995) and hotels (Nicolau, Mellinas, & Martín-Fuentes, 2020).

3.1.2 Rationale and Aims

In summary, information intervention strategies are an invaluable tool for improving energy sustainability. However, reviews of intervention effectiveness have revealed many issues, such as problematically wide variations in evaluated effectiveness and inconsistencies in implementation, even within supposedly similar forms of information provision. While the effectiveness of information interventions is subject to the ‘type’ of information given (e.g., pecuniary, social-normative), many other visual parameters of information communication have been shown to have potentially substantial effects on the perception of information – including the type of representation and organization (table, textual, or graphical), as well as other low-level visual aesthetical parameters such as colour, size, and/or spatial positioning.

However, despite the primarily visual nature of information strategies, research into the effects of parameters associated with visual information communication has been reviewed to be severely neglected within the energy sustainability literature. Due to a lack of empirical data examining the impacts of such parameters, it remains unclear as to what effects differences in these parameters may induce, as well as to what degree of impact these factors may contribute towards an intervention’s outcomes. Thus, to address the gaps in the existing literature, the current study aims to investigate the information communication outcomes of an existing information behavioural intervention. Following a previous exploratory study employing neurophysiological eye-tracking measures, the current study employs stimuli that are adapted from existing real-world implementations of information provision (e.g., utility bills in Singapore). By evaluating similar visual information provisions (to that of existing implementations), insights gained on the potential factors highlighted in the previous section

can be more readily inferred, with significantly less ambiguity relative to extrapolation from a visually less similar experimental configuration. Moreover, the use of existing real-world usage of intervention implementations may likewise reveal potential, ecologically valid specificities with real ramifications for ongoing conservation efforts.

For this study, the utilities billing format of feedback information, as implemented in Singapore, was selected to be employed as the experimental stimuli of choice. Specifically, the recently updated (i.e., 2016) billing format of household utilities in Singapore (see *section 2.2.3*) includes multiple information elements that represent types of information (i.e., pecuniary/physical/socio-normative, or graphical/textual) that would allow for the potential impacts of these parameters to be assessed. Moreover, the presence of multiple utility types (e.g., energy and water) in the same billing would also allow for the evaluation of potential socio-psychological effects that may arise from the existing information provision format to be observed. In particular, within the context of domestic usage, both energy and water consumption are linked to a certain degree, with water heating representing one of the most energy intensive activity in households (Fuentes, Arce, & Salom, 2018; Haines, Kyriakopoulou, & Lawton, 2019; Hernandez & Kenny, 2012; Janssen, 2004). However, this relationship is not particularly visible, with a lack of any mention made in the feedback information provided (i.e., utilities billing). As such, determining how individuals perceive either utility individually and in relation to each other would be useful, given that the nature of interrelations between energy and water relationship is likely to have a notable effect on domestic energy efficiency.

With regards to information provision as per a household utilities billing format, ideally the provision of feedback information should result in fairly ‘accurate’ perceptions in the end-users (i.e., households). However, due to a lack of relevant empirical data, it is currently unclear as to how different visual information communication parameters may influence the outcomes

on aspects such as perception and judgments. For instance, whether the spatial positioning of information may influence perceptual judgements and impact people's impetus to behave (e.g., energy consumption). One example of how spatial position may influence efficiency judgements may be via differences in attentional saliency such as in marketing research where visual salience of different convenience goods was manipulated by varying its' placement (top vs. lower shelf) (Chandon & Wansink, 2002).

Another example may be via the conceptual metaphor theory which refers to the understanding of one idea (conceptual domain) in terms of another (Lakoff & Johnson, 1980). In particular, the theory states that abstract concepts are represented by metaphors which provide grounding by connecting the abstract concepts to more concrete representations. This theory is stated to originate from evidence of metaphorical expressions (e.g., the cost is rising), where the structure inherent within a concrete concept is mapped onto an abstract concept. Concrete concepts take their structure from image schemas (Grady, 2005; Johnson, 2013) of which are patterns of multi-modal activation stemming from repeated experiences. Conversely, abstract concepts are proposed to be grounded metaphorically in embodied and situated knowledge (Lakoff, Johnson, & Sowa, 1999), with familiar concrete concepts being used to enable comprehension of unfamiliar abstract concepts (Yin, Su, & Ye, 2013).

Particularly, spatial metaphors are proposed to play a crucial role in the formation of abstract concepts (Lakoff & Johnson, 2008; Wu et al., 2016), given that spatial concepts present one of the primary and most familiar concepts to humans. For instance, "vertical spatial metaphor" relating to upper and lower (top and bottom) spatial positions are the most basic metaphor in spatial metaphors, and thus could be mapped onto abstract concepts of a target conceptual domain. Examples include affective experience being understood vertically as "good is up" and "bad is down", helping the construction of abstract concepts such as

“promotion and demotion” (Bergen, Lindsay, Matlock, & Narayanan, 2007; Casasanto, 2009; Giessner & Schubert, 2007; Meier, Hauser, Robinson, Friesen, & Schjeldahl, 2007).

In previous behavioural studies, the processing of the abstract concept of “power” was observed to be able to activate an underlying vertical spatial image schema, with impacts on both judgements and behavioural responses (e.g., speed and accuracy of responses) when the mapping of these abstract concepts was congruent with the visual spatial position of presentation (Schubert, 2005; Zanolie et al., 2012). While the mapping of abstract concepts such as “efficiency” with vertical spatial positions is relatively unexplored within the literature, the associations of verticality and positive/negative concepts may reasonably result in effects on perception and judgement, given also the findings in Study 1 where electricity and water utility graphs - differing primarily in spatial position (top/bottom) - was reported to also differ in gaze duration and frequency.

Thus, to investigate the information communication outcomes on perception and judgement, the judgement behaviour of the following information variables – electricity and water utility consumption efficiency ratings – are measured. In addition, this study also aims to characterize the effects of information communication on information cognition. To achieve these aims, judgement of an ‘overall’ household efficiency (i.e., overall utility consumption efficiency) was measured as well. The understanding of the process of abstract transformation, and application of information, is important, as it would provide insights into how such information is encoded, stored and utilized cognitively, as well as reveal any potential problems with the existing information provision formats and the ramifications for intervention outcomes. Lastly, I also investigate whether visual spatial positioning of either utility’s information plays a role in the perception and judgement of information.

To guide the current experiment, several hypotheses and their respective rationales are outlined below:

- To determine if the perception of provided information (e.g., utilities consumption feedback) is accurate, specifically such that subjective ratings of either utility's efficiency would parallel objective consumption levels, of only the relevant utility type, the following hypotheses were made:
 - **H1.1:** Higher levels of depicted electricity consumption will be associated with lower levels of electricity efficiency ratings.
 - **H1.2:** Electricity efficiency ratings will be predominantly explained by electricity consumption information, relative to water consumption information and an interaction term between both utilities' consumption information.
 - **H1.3:** Higher levels of depicted water consumption will be associated with lower levels of water efficiency ratings.
 - **H1.4:** Water efficiency ratings will be predominantly explained by water consumption information, relative to electricity consumption information and an interaction term between both utilities' consumption information.
- Next, to characterize how both utilities' information is cognitively utilized, relative to each other, a 'combined' overall judgement of utilities efficiency (i.e., overall utility efficiency ratings) between varying pairs of consumption were conducted with counterbalancing of conditions. This overall efficiency rating task also serves to illustrate how information provided within the experimental stimuli is stored and retrieved for usage. As the interrelations between both utility types are not explicitly communicated within the current feedback information format, it is assumed that both utilities' information was intended to have "equal contribution" in cognitive functions relating to both,

such as in the case of generating a ‘combined’ overall judgement of household utilities efficiency. To test these assumptions, the following hypotheses were formulated:

- **H2.1:** Overall efficiency ratings will be significantly associated with electricity and water consumption, as well as an interaction term between both utilities.
 - **H2.2:** Overall efficiency ratings will be predominantly explained by an interaction term between both utilities’ consumption information.
 - **H2.3:** The differences in variance explained by both electricity and water consumption information will be small or inconsistent (e.g., no complete or conditional dominance of one over the other).
- Finally, to investigate whether lower-level visual parameters such as spatial positioning of either utility’s information would play a significant role in perception of information and subsequent judgements, the position of either utility (electricity and water) was manipulated, such that either utility would be randomly presented in both the top and bottom positions at equal frequencies. Should spatial position have an impact, such as biasing evaluations of efficiency towards information location in a specific position, such effects may manifest on judgments of a specific utility (i.e., water or electricity). The following hypothesis was formulated to be tested in this current study:
 - **H3:** Spatial position will be significantly associated with specific utility efficiency ratings (electricity and water).

3.2 Design and Methodology

3.2.1 Participants

A total of 380 participants (186 females; $M_{\text{age}} = 37.16$ years, $SD = 10.63$) were recruited via the online survey development platform Qualtrics (Qualtrics, 2017) to participate in this study. The study was approved by the Nanyang Technological University Institutional Review Board and all procedures were performed according to guidelines. The objectives of the study were kept vague in recruitment advertisements to ensure minimal self-selection bias.

A power analysis was conducted using the power analysis calculator from (Judd et al., 2017). With an estimated effect size of approximately 0.4 (Brysbaert, 2019) and expected power of 0.8, the minimum number of participants needed to power the study is 47.8. Using the same model, the power of the current study in a reverse analysis is 0.942, which is above the recommended level of 0.8 (Brysbaert, 2019; Judd et al., 2017).

3.2.2 Experimental setup and stimuli

The experimental stimuli consist of a hypothetical households' utilities bill – modelled after the actual billing format currently in use by the Singapore utilities company (*SP services*) (see Figure 11) since 2016 (EMA, 2016). Each bill includes a hypothetical household's consumption information of both water and electricity utility type for that current month. Consumption information of each utility is presented in text as both pecuniary cost (in *SGD*) and physical units (*kWH/L*). Graphical representation (i.e., bar charts) of each utilities' consumption information showed monthly consumption trends for a historical period of up to 6 months next to the text and physical units. The consumption of each individual month is represented as a separate bar along the horizontal 'x' axis. Furthermore, each chart also features a solid and dotted horizontal line to represent (hypothetical) national and neighbourhood averages respectively. Both (national and neighbourhood) averages were depicted to be

similar/equal to each other across all experimental conditions and levels for experimental design purposes.

Figure 11. An example image of the actual, revised Singapore utilities billing information, adapted for use as experimental stimuli in the current study.

To determine if differences in information pertaining to consumption and utility type has any effect on perception and decision making, the consumption levels of either utility (electricity and water) was set to either one of three pre-defined levels: low, average and high, representing either 50% lower (low), equal (average), or 50% higher (high) utility consumption relative to the national/neighbourhood averages. To understand how information may be utilized in cognitive processes, contrasts between varying combinations of each utility consumption levels were conducted. To examine the potential effects of spatial position on perception, the relative order of each utility's placement on the stimuli (first/top, or second/bottom) were varied across trials. As such, the current study employed a 3

(consumption level: low, average, high) by 2 (utility type: electricity, water consumption) by 2 (spatial position: top, bottom) within-subjects design.

3.2.3 Procedure

The experiment was conducted online through the survey development platform Qualtrics™. Participants were first presented with a brief introduction of the study and consent form, followed by the display of the experimental task instructions and a short questionnaire on their background (i.e., gender, age, education), all in the absence of a time limit. They were next exposed to an initial ‘training’ phase of 4 timed practice trials (presented in a randomized order) where upon completion of the training phase, participants were once again presented with a similar untimed task instruction page, which notified them that were allowed a break prior to the start of actual experimental trials (Figure 12).

Figure 12. Experimental procedure sequence of events.

Each participant completed an equal number of actual experimental trials consisting of exposure to all treatment levels. In each trial, participants were presented on-screen with the experimental stimuli for 10 *seconds* before being asked to judge and rate the efficiency of the

household on 3 aspects: overall, electricity and water. Responses were all recorded on an on-screen numeric slider scale (i.e., 0 = highly inefficient, 50 = average, and 100 = highly efficient) (see *appendix C*). Each question appeared on a separate page in randomized order with no time limit imposed (see Figure 11).

3.3 Data Analysis and Results

For data analysis, linear mixed-effects model (LMM) analyses (Laird & Ware, 1982) with a Maximum Likelihood estimation method was employed via *R* statistical software (R Core Team, 2017) and the statistical package ‘*lme4*’ (Bates et al., 2015). To evaluate significance of effects in the models, Satterthwaite’s method ANOVA using the ‘*lmerTest*’ package (Giesbrecht & Burns, 1985; Hrong-Tai Fai & Cornelius, 1996; Kuznetsova et al., 2017) was selected. Model effect size estimates were obtained using the “*MuMIn*” statistical package and subsequent post-hoc contrasts of interaction effects via estimated marginal means were obtained using the statistical package ‘*emmeans*’ (Lenth, 2019) with Tukey’s adjustment.

For each of the 3 different measures of efficiency (i.e., overall, electricity, water) (see *appendix C*), the following variables were modelled as fixed effects in the analyses: electricity consumption level, water consumption level, and spatial order, with each individual participant modelled as a random effect. Model fit comparisons between nested full and null models were done by comparing Akaike information criterion (AIC) and Bayesian information criterion (BIC) values, with statistical comparisons conducted via chi-square tests. All final models selected were observed to significantly improve model fit indices against their respective null equivalents, indicating the modelled effects of interest (e.g., utility consumption) to significantly contribute to subjective rating outcomes (Table 2).

Table 2. Comparisons of model fit indices between full and reduced LMM models (*p < .05,

p < .01, *p < .001).

DV	Model	AIC	BIC	χ^2	df	p
Overall	Null	113022	113044	6519.9	9	<.001***
	Full	106520	106610			
Electricity	Null	119446	119469	6681.5	9	<.001***
	Full	112783	112873			
Water	Null	120224	120247	6654.6	9	<.001***
	Full	113588	113678			

To evaluate the relative importance of predictors within the LMM models, a dominance analysis (DA) was employed via the *R* statistical package ‘*dominanceanalysis*’ (Azen & Budescu, 2003, 2006; Azen & Traxel, 2009; Budescu, 1993; Luo & Azen, 2013). DA is employed in linear regression models to rank predictors in terms of relative importance via the comparison of contributions each predictor makes to the variance reproduced (or explained) by different subset models consisting of subsets of the predictors. The additional contribution by a predictor is measured as the increase in explained variance (R^2) when a predictor is added to a given subset model. Extensions of the methodology to hierarchical linear models were employed in the following analyses (Luo & Azen, 2013) using *S&B R²*: an analogue R^2 index term that computes for the proportional modelled variance in multi-level linear models (Snijders & Bosker, 1994).

3.3.1 Electricity Efficiency

For judgements of electricity efficiency, electricity consumption information was hypothesized in *H1.1* to have a significant effect. Overall, the results of the LMM analyses

(conditional $R^2 = .48$) revealed a significant main effect of both electricity and water consumption levels on electricity efficiency ratings, qualified by a significant two-way interaction ($F_{4,13300} = 100.23$, $p = <.001$). Main effect analyses of spatial order, contrary to hypothesis $H3$, were however found to not be significant ($F_{1,13300} = 2.39$, $p = .12$).

Figure 13. LMM plot of ‘electricity efficiency’ means across water utility consumption levels, grouped by levels of electricity utility consumption. Bands around each line denote the S.E.

In particular, electricity efficiency ratings were found to increase as electric consumption levels decreased (see Figure 13), such that the household was judged by participants to be more efficient, in-line with predictions made for $H1.1$. This observation indicated that the experimental manipulations were working as desired, reflecting that participants understood the experimental task requirements and were sensitive to the different consumption levels employed.

Results of a DA conducted on the LMM model of electricity efficiency judgment ratings (see the last five columns of Table 3) indicated the interaction between electricity and water

utility consumption (X_4) to completely dominate electricity consumption (X_1), water consumption (X_2) and spatial position (X_3), contrary to predictions made for *H1.2*. Electricity consumption was observed to completely dominate water consumption and spatial position, while spatial position was found to be completely dominated by water consumption.

Table 3. Dominance analysis results for the LMM model of electricity efficiency.

Subset model	Additional Contribution of					Additional Contribution of				
	<i>R&B</i> R^I_2	X_1	X_2	X_3	X_4	<i>S&B</i> R^I_2	X_1	X_2	X_3	X_4
$k = 0$ average	0.000	0.373	0.003	0.000	0.395	0.000	0.312	0.003	0.000	0.331
X_1	0.373		0.003	0.000	0.022	0.312		0.003	0.000	0.018
X_2	0.003	0.373		0.000	0.391	0.003	0.312		0.000	0.328
X_3	0.000	0.373	0.003		0.395	0.000	0.312	0.003		0.331
X_4	0.395	0.000	0.000	0.000		0.331	0.000	0.000	0.000	
$k = 1$ average		0.249	0.002	0.000	0.269		0.208	0.002	0.000	0.225
X_1, X_2	0.377			0.000	0.018	0.315			0.000	0.015
X_1, X_3	0.373		0.003		0.022	0.313		0.003		0.018
X_1, X_4	0.395		0.000	0.000		0.331		0.000	0.000	
X_2, X_3	0.003	0.373			0.391	0.003	0.312			0.328
X_2, X_4	0.395	0.000		0.000		0.331	0.000		0.000	
X_3, X_4	0.395	0.000	0.000			0.331	0.000	0.000		
$k = 2$ average		0.124	0.001	0.000	0.144		0.104	0.001	0.000	0.120
X_1, X_2, X_3	0.377				0.018	0.315				0.015
X_1, X_2, X_4	0.395			0.000		0.331			0.000	
X_1, X_3, X_4	0.395		0.000			0.331		0.000		
X_2, X_3, X_4	0.395	0.000				0.331	0.000			
$k = 3$ average		0.000	0.000	0.000	0.018		0.000	0.000	0.000	0.015
All	0.395					0.331				
Overall average		0.249	0.002	0.000	0.269		0.208	0.002	0.000	0.225

Note: X_1 = Electricity Consumption; X_2 = Water Consumption, X_3 = Spatial position, X_4 = Interaction between Electricity and Water consumption.

Critically, the association of electricity consumption levels with electricity efficiency ratings appeared to also be dependent on water consumption levels, such that mean estimate (electricity) efficiency ratings at low electricity consumption levels were observed to be significantly higher when water consumption was low, relative to when water consumption

was either average ($z = -17.04, p < .001$) or high ($z = -19.30, p < .001$). No statistically significant efficiency rating differences were observed between average and high-water consumption levels ($z = -2.27, p = .362$).

From the analyses, it was also observed that electricity efficiency ratings at average electricity consumption levels were significantly lower when water consumption levels were low, relative to when water consumption levels were average ($z = 3.937, p < .01$). However, no significant differences were observed between when water consumption levels were high, relative to when water consumption levels were average ($z = -1.455, p = .876$) or low ($z = 2.482, p = .24$). Likewise, at high electricity consumption levels, ratings of electricity efficiency were significantly lower for when water consumption levels were low, relative to when water consumption levels were average ($z = 3.705, p < .01$). No significant differences between high water consumption levels with both average ($z = -1.601, p = .805$) and low consumption levels ($z = 2.104, p = .471$) were observed.

3.3.2 Water Efficiency

Likewise, for efficiency judgements of water utility, a primarily significant effect of water consumption information was expected in hypothesis *H1.3*, with hypothesis *H1.4* positing water consumption to predominantly contribute to the variance explained in the model analyses. Overall, the results of the LMM analyses for water efficiency ratings indicated a significant main effect of both electricity and water utilities' consumption levels, also qualified by a significant two-way interaction ($F_{4,13300} = 49.30, p = <.001$) (conditional $R^2 = .46$). No statistically significant effects were observed for the spatial order variable ($F_{1,13300} = 2.80, p = .09$), contrary to *H3*. In particular, the results were supportive of *H1.3*, revealing the relationship between water efficiency ratings and water utility consumption to be such that lower consumption levels were judged to be more efficient (Figure 14).

Figure 14. LMM plot of ‘water efficiency’ means (y-axis) across electricity utility consumption levels (x-axis), grouped by levels of water utility consumption. Bands around each line denote the S.E.

The results of a DA conducted on the LMM model of water efficiency judgment ratings (see the last five columns of Table 4) revealed the interaction between electricity and water utility consumption (X_4) to completely dominate electricity consumption (X_1), water consumption (X_2) and spatial position (X_3), contrary to predictions made in *H1.4*. Water consumption was also observed to completely dominate electricity consumption and spatial position, while electricity consumption completely dominated spatial position.

Importantly, the relationship between water consumption and water efficiency was found to be dependent on electricity consumption levels. For instance, at low water consumption levels, the mean efficiency ratings of water utility were observed to be significantly higher (more efficient), when electricity consumption levels were low as well, relative to either average ($z = 16.271, p < .001$) or high ($z = 16.752, p < .001$) electricity consumptions. Likewise, when water consumption levels were high, the mean efficiency ratings of water utility were observed to be significantly lower (e.g., inefficient), when electricity consumption levels were also high, in comparison to both average ($z = -6.748, p < .001$) and low ($z = -8.944, p < .001$)

electricity consumption. Conversely, when water consumption levels were average, no significant differences in water efficiency ratings were observed across electricity consumption levels.

Table 4. Dominance analysis results for the LMM model of water efficiency.

Subset model	Additional Contribution of					Additional Contribution of				
	<i>R&B</i> R^I_2	X_1	X_2	X_3	X_4	<i>S&B</i> R^I_2	X_1	X_2	X_3	X_4
$k = 0$ average	0.000	0.012	0.373	0.000	0.394	0.000	0.010	0.322	0.000	0.340
X_1	0.012		0.373	0.000	0.382	0.010		0.322	0.000	0.330
X_2	0.373	0.012		0.000	0.021	0.322	0.010		0.000	0.018
X_3	0.000	0.012	0.373		0.394	0.000	0.010	0.322		0.340
X_4	0.394	0.000	0.000	0.000		0.340	0.000	0.000	0.000	
$k = 1$ average		0.008	0.249	0.000	0.265		0.007	0.215	0.000	0.229
X_1, X_2	0.385			0.000	0.009	0.332			0.000	0.008
X_1, X_3	0.012		0.373		0.382	0.010		0.322		0.330
X_1, X_4	0.394		0.000	0.000		0.340		0.000	0.000	
X_2, X_3	0.373	0.012			0.021	0.322	0.010			0.018
X_2, X_4	0.394	0.000		0.000		0.340	0.000		0.000	
X_3, X_4	0.394	0.000	0.000			0.340	0.000	0.000		
$k = 2$ average		0.004	0.124	0.000	0.137		0.003	0.107	0.000	0.119
X_1, X_2, X_3	0.385				0.009	0.332				0.008
X_1, X_2, X_4	0.394			0.000		0.340			0.000	
X_1, X_3, X_4	0.394		0.000			0.340		0.000		
X_2, X_3, X_4	0.394	0.000				0.340	0.000			
$k = 3$ average		0.000	0.000	0.000	0.009		0.000	0.000	0.000	0.008
All	0.394					0.340				
Overall average		0.008	0.249	0.000	0.265		0.007	0.215	0.000	0.229

Note: X_1 = Electricity Consumption; X_2 = Water Consumption, X_3 = Spatial position, X_4 = Interaction between Electricity and Water consumption.

3.3.3 Overall Efficiency

To understand how either utilities' (water or electricity) information is cognitively perceived and utilized, an analysis of subjective judgements of overall efficiency – that which would require the utilization of consumption information of both utility types – was conducted. Overall, the results of the LMM analysis on overall efficiency ratings indicate the main effects

of both electricity and water consumption to be significant, qualified by a significant two-way interaction ($F_{4,13300} = 169.15, p < .001$) (conditional R^2 of .52) in line with *H2.1*. Spatial order main effects were observed to be non-significant ($F_{1,1330} = 2.41, p = .12$). More specifically, overall efficiency ratings were observed to improve (i.e., higher efficiency) significantly as electricity consumption level decreased – a relationship that was also observed to be dependent on water consumption levels, such that reductions in water consumption levels were associated with significant increases in overall efficiency ratings as well (Figure 15).

Figure 15. LMM plot of ‘overall efficiency’ means (y-axis) across water utility consumption levels (x-axis), grouped by levels of electricity utility consumption. Bands around each line denote the S.E.

Subsequent findings of a DA on the LMM model of overall efficiency judgment ratings (see the last five columns of Table 5) revealed the interaction between electricity and water utility consumption (X_4) to completely dominate electricity consumption (X_1), water consumption (X_2) and spatial position (X_3), in line with predictions made in *H2.2*. Electricity consumption was also observed to completely dominate water consumption, although

differences in additional contributions to variance explained were found to be quite low (R^2 differences of $< .052$), in line with predictions in *H2.3*. Both electricity and water consumption were similarly observed to completely dominate spatial position.

Table 5. Dominance analysis results for the LMM model of overall efficiency.

Subset model	Additional Contribution of					Additional Contribution of				
	$R\&B$ R^2_2	X_1	X_2	X_3	X_4	$R\&B$ R^2_2	X_1	X_2	X_3	X_4
$k = 0$ average	0.000	0.204	0.152	0.000	0.387	0.000	0.155	0.115	0.000	0.294
X_1	0.204		0.152	0.000	0.183	0.155		0.115	0.000	0.139
X_2	0.152	0.204		0.000	0.236	0.115	0.155		0.000	0.179
X_3	0.000	0.204	0.152		0.387	0.000	0.155	0.115		0.294
X_4	0.387	0.000	0.000	0.000		0.294	0.000	0.000	0.000	
$k = 1$ average		0.136	0.101	0.000	0.269		0.104	0.077	0.000	0.204
X_1, X_2	0.356			0.000	0.031	0.271			0.000	0.024
X_1, X_3	0.204		0.152		0.183	0.155		0.115		0.139
X_1, X_4	0.387		0.000	0.000		0.294		0.000	0.000	
X_2, X_3	0.152	0.204			0.236	0.115	0.155			0.179
X_2, X_4	0.387	0.000		0.000		0.294	0.000		0.000	
X_3, X_4	0.388	0.000	0.000			0.294	0.000	0.000		
$k = 2$ average		0.068	0.051	0.000	0.150		0.052	0.038	0.000	0.114
X_1, X_2, X_3	0.356				0.031	0.271				0.024
X_1, X_2, X_4	0.387			0.000		0.294			0.000	
X_1, X_3, X_4	0.388		0.000			0.294		0.000		
X_2, X_3, X_4	0.388	0.000				0.294	0.000			
$k = 3$ average		0.000	0.000	0.000	0.031		0.000	0.000	0.000	0.024
All	0.388					0.294				
Overall average		0.136	0.101	0.000	0.269		0.104	0.077	0.000	0.204

Note: X_1 = Electricity Consumption; X_2 = Water Consumption, X_3 = Spatial position, X_4 = Interaction between Electricity and Water consumption.

3.4 Discussion

Aiming to better understand the potential factors of variability in informational feedback strategies, the current study examined how perception and judgement decision making is influenced in an instance of feedback intervention. Although previous research and usage of behavioural information intervention strategies in conservation predominantly involved visual information provision, the literature is largely bereft of any relevant empirical data that may be used to understand and predict the effects of varying visual parameters on cognition, perception and behavioural outcomes. Reviews of information communication research have also indicated effects to potentially be substantial, suggesting an urgent need to examine and characterize existing and future methodology.

To re-cap, the current study aims to characterize the provision of feedback information as employed in utility bills in Singapore. Specifically, the provision of utilities' historical consumption should correspondingly result in 'accurate' perceptions of consumption and efficacy, i.e., with subjective ratings paralleling objective levels of consumption. Results of the current study have indicated that while the judgments of efficiency of either utility (electricity or water) were significantly influenced by relevant consumption information of the same utility type, there is existing interference by consumption information from the other non-relevant utility. In particular, the analysis of relative importance of predictors revealed the interaction term between both utilities as the most relevant predictor in predicting individual efficiency ratings, followed by the relevant utility's consumption information as the next most important predictor.

Although both energy and water utilities were noted in previous publications to be highly interrelated (e.g., water is consumed in energy generation and energy is consumed in household activities such as water heating), this relationship was not explicitly communicated within the current context of feedback billing information (e.g., in contrast to appliances, or activity levels

of specificity). Thus, for a naïve observer's (i.e., non-expert) evaluative judgements on individual utility ratings, it was expected that there would be minimal relevance of the other non-relevant utility's consumption information.

One potential explanation proposed to underlie this observed phenomenon includes anchoring effects (e.g., Furnham & Boo, 2011) – such that the exposure to a non-relevant utility's consumption information might have influenced subsequent judgments of the relevant utility, leading to distorted judgements of efficiency. However, as no statistically significant effect of visual spatial order of utility type was found in the current results, ordering and anchoring effects may not necessarily underlie the mechanism in which either utility's consumption information influences each other. Instead, the underlying mechanism may be more akin to that of context effects, such as assimilation or contrast effects in which the enhancement or diminishment of a perceived quality (e.g., consumption efficiency of a utility) is biased towards the position of a context stimulus, relative to normal (Greifeneder, Bless, & Fiedler, 2017; Kenrick & Gutierrez, 1980; Lord, Ross, & Lepper, 1979; Schwarz, Strack, & Mai, 1991).

For instance, the evaluation of a utility's consumption may be biased towards being more negative or positive, depending on the context stimulus (i.e., the other utility's consumption being positive/low consumption and high efficiency or negative/high consumption and low efficiency). A potential psychological model used to explain contrast effects is the inclusion/exclusion model (Bless & Schwarz, 2010). Specifically, the model assumes that feature-based evaluative judgements require a mental representation of the target of judgment and of a standard to which the target is compared against. The representations are context sensitive and based on the information that is most accessible at the time (e.g., that readily comes to mind first in that specific moment of evaluation and draws attention). The accessible information that is used to construct the representation of the target results in assimilation

effects, while use of the information to form a representation of the standard of comparison results instead in contrast effects. How the information is used depends on an individuals' beliefs about whether the information was brought to mind by some irrelevant influence, the perceived representativeness (for the target), as well as norms that influence the perception of appropriateness of the manner the information is used.

Alternatively, the distortion may also be attributed to the phenomenon of selective attention (or the lack thereof) as theorized in perceptual-load theory; where perceptual and cognitive demands influence the processing or inhibition of distractor interference (Murphy, Groeger, & Greene, 2016). Within the context of the current study's experimental task which requires information (i.e. consumption levels of both utilities) to be held in one's working memory, cognitive load requirements may plausibly have been high enough to cause distractor inhibition to fail (Lavie, 2010), resulting in distortions of utility efficiency judgements to manifest.

Another possibility may be due to memory biases such as the positivity offset effect and/or negativity bias (Ito & Cacioppo, 2005; Norris, Larsen, Crawford, & Cacioppo, 2011), where the emotional valence of 'positive' low consumption levels and/or correspondingly 'negative' high consumption levels could have resulted in distorted judgement behaviours. Other phenomena may include some form of visual search asymmetry effect – defined as a change in search efficiency that occurs when the target and the distractor switch roles (Jiye, Shen & Reingold, 2001; Treisman & Souther, 1985).

Contrary to subjective efficiency evaluations of a specific utility type, judgements of an 'overall' efficiency should implicate the consumption information of both utilities instead; thus, one would expect the information of both utility types to both be significant drivers in influencing rating outcomes. Moreover, as there is little information presented detailing the potential qualitative and quantitative differences of either utility, it was assumed that a naïve

observer would perceive both utilities then to be fairly equal in a judgement of overall utility efficiency. From the results of the experiment, both electricity and water consumption information was indeed found to have a significant impact on overall efficiency ratings, with the interaction term between both utility types observed to be the most relevant predictors. Differences in relevance between the main effects of either utility's consumption information were also subsequently found to differ slightly, with the estimated variance explained by either term to differ by 5.2% or less.

Taken together, the results suggest the distortions observed in individual assessments of utility efficiency to be due to differences in task characteristics and/or cognitive operations required (i.e., cognitive manipulation of information to obtain an 'integrated' score or encoding and recalling information accurately). As such, the findings of the current study reveal several implications for ongoing information intervention efforts. Firstly, the distortions in individual utility efficiency assessments in response to existing formats of feedback information such as those in utility bills is likely to result in inaccurate perceptions of self-consumption behaviour. Such effects may be akin to that of moral licensing, where the positive behaviour (e.g., efficient curtailment) in one domain may be unconsciously used by an individual to offset negative ones, leading to issues such as the rebound phenomenon (where energy or even water savings are reduced). Moreover, the incorrect assessment of energy and water utility usage may hamper further information provision efforts, such as reducing the urgency or removing the impetus to act upon signals of unsustainable resource consumption.

Secondly, given that the current findings suggest a role of task demands in the manifestation of information perception distortions, it may be plausible that one remedy for the observed phenomenon is to actively alter the path of intrinsically generated goals with regards to information acquisition and usage. For instance, consider the naïve individual who receives a utility bill in the mail. The response to the provision in feedback information,

unguided, will potentially be to assess the usage of electricity and/or water of the household to determine how ‘efficient’ it is. However, should there be additional information included to guide the formation of such unfettered objectives, such as the inclusion of text forewarning about such distortions, the individual may instead be prompted to consciously formulate his or her assessment of consumption more carefully. Other countermeasures that may be devised may also include the use of cues such as colour to provide irrefutable proof of unsustainable consumption behaviours.

In conclusion, the current findings reveal a potentially significant role of visual information perception and cognition in determining behavioural outcomes. Specifically, the lack of consideration for visual information parameters in existing and ongoing implementations may result in unwanted perceptual distortions, contributing to potential variations in intervention effectiveness. As such, it is suggested that the integration of more diverse cross-disciplinary approaches into sustainable behaviour research may help to provide the necessary perspectives in which potential metaphorical ‘blind spots’ may be eliminated, strengthening existing sustainability efforts as a whole.

Beyond the scope of addressing methodological assumptions of informational interventions, the use of multidisciplinary visual perception approaches may also be adopted to develop other forms of interventions (i.e., non-informational). In particular, the following study evaluates the use of intrinsic psychological associations and visual perception as a potential non-informational intervention strategy. Similar to the current study, intrinsic neurophysiological characteristics such as circadian processes are integrated into this approach as a means to better elucidate the key factors of intervention success.

4 Non-information interventions: Visual colour perception, Thermal perception and Physiology

4.1 Introduction and Literature Review

4.1.1 Brief Summary and Background

The use of non-informational strategies such as nudging typically revolves subconsciously influencing behaviour to change, for instance via engaging decision-making heuristics (e.g., defaults, social proof, framing), or through altering perception such as by changing the layouts and features of different environments. While information strategies for energy conservation play a significant role in previous and ongoing efforts, the use of non-informational strategies is also vital in ensuring that conservation outcomes such as reduced usage are met, as much of our daily behaviours are entrenched in routines that are engaged quickly and automatically with little attentive decision-making (Becker, 1992; Heimlich & Ardoin, 2008).

To this end, the current study aims to investigate a non-informational visual perception intervention strategy employing a disparate psychological mechanism to induce energy-efficient and conservation behaviour. In particular, the use of multisensory perception is investigated as a mechanism in which thermal comfort and perception can be influenced to reduce reliance on space-cooling system usage in households.

4.1.2 Building Thermal Conditioning and Energy Consumption

Buildings represent a significant proportion of total energy consumption and greenhouse gas emissions globally. Within the European Union, US and UK, both residential and commercial buildings are noted to contribute up to 40% of the final energy demand, whilst generating roughly a third of the greenhouse emissions (Balaras, Droutsas, Dascalaki, & Kontoyiannidis, 2005; Costa, Keane, Torrens, & Corry, 2013; Fiaschi, Bandinelli, & Conti,

2012; Pérez-Lombard, Ortiz, & Pout, 2008). In Southeast Asia, buildings consume an approximate 32% and 24% of total electricity sales in Malaysia and in Thailand respectively (Al-Obaidi, Ismail, & Abdul Rahman, 2014; Qi Jie Kwong, Nor Mariah Adam, & B.B. Sahari, 2014), while Singapore, the world's fourth leading financial centre reported energy consumption to be 15.6% for households and 36.4% for commerce and services-related sectors (EMA, 2016).

As thermal comfort is a highly important consideration of building occupants – being valued over other environmental aspects such as air-quality, visual and acoustic comfort (Frontczak & Wargocki 2011), while also being highly influential on human performance and productivity (F. Zhang, de Dear, & Hancock, 2019) – it comes as little surprise that the operation of space heating and cooling systems is identified as a major driver of energy usage in this sector (Balaras et al., 2005; Costa et al., 2013; Fiaschi et al., 2012; Pérez-Lombard et al., 2008; Qi Jie Kwong et al., 2014). Furthermore, increasing affluence, rapid urbanization, as well as increased instances of extreme weather conditions (Bouwer, 2019) have all played a part in increasing the proliferation of thermal conditioning systems and their usage, further exacerbating current global energy demand and in the projected future.

With regards to the amount of energy saved by improving the comfortable temperature of air-conditioning systems, estimates are difficult and complex given the numerous factors involved, including the system efficiency, model and build, maintenance condition, system size and home size matched, home envelop type, and the outdoor weather. From government websites such as the National Environment Agency in Singapore, every degree above 25 °C may help save up to \$25 a year (based on average 2012 electricity tariff of \$0.2989 per kWh, assuming a single-split, 1000W air-conditioner and/or a 31W electric fan where relevant used for 365 days a year) (National Environmental Agency, 2021). Similarly, the US Department of Energy states estimates of “*about 1 percent for each degree (f) of thermostat adjustment per 8*

hours” (Department of Energy, 2012), while the Bureau of Energy Efficiency agency of the Government of India (Ministry of Power, 2018) suggests that reduction in air-conditioning to 24 °C from the conventional 18 to 21 °C can result in 24 percent of energy savings.

Consequently, conservation strategies aiming to mitigate energy consumption in buildings have often focused on addressing thermal conditioning needs. While multiple strategies have been explored within the literature, including the use of building envelopes (e.g. Yu, Yang, Tian, & Liao, 2009), reflective coatings (e.g. Joudi, Svedung, Cehlin, & Rönnelid, 2013), model predictive control of thermal conditioning systems (e.g. Široký, Oldewurtel, Cigler, & Prívar, 2011), and optimized automated control systems (e.g. Marinakis, Doukas, Karakosta, & Psarras, 2013) – the results have been unsatisfactory with even supposedly predictive standards of indoor comfort (e.g. ASHRAE 55) resulting in high levels of dissatisfaction instead (Mishra, Derks, Kooi, Loomans, & Kort, 2017). For instance, the use of supposedly efficient automated and/or standardized thermal conditioning control systems is also observed to result in lower occupant satisfaction – an unintentional result from occupants’ perceived loss of control over their surroundings (Wagner, Gossauer, Moosmann, Gropp, & Leonhart, 2007). Hence, an alternative solution to improving efficiency of thermal conditioning systems is still required.

4.1.3 Multimodal Perception: Thermal and Visual Colour Perception

The findings of ongoing neuroscience research have shown perception to be multimodal, i.e., that the human brain processes sensory input from one modality in relation to input registered in another sensory modality (Spence & Driver, 2004; Welch & Warren, 1986). This multimodal perception has been observed to occur across a large range of sensory modalities, including auditory, visual, gustatory (Bayarri, Calvo, Costell, & Durán, 2001), olfactory (Zellner & Kautz, 1990), and tactile sensory modalities (Ernst, Banks, & Bühlhoff, 2000; Falchier, Clavagnier, Barone, & Kennedy, 2002; Foxe et al., 2002; Rockland & Ojima,

2003), resulting in significantly varied subjective evaluations. For instance, the hue of a food item alters perceptions of taste; where the very same wine is judged as being significantly better tasting under red than green ambient room lighting (Oberfeld, Hecht, Allendorf, & Wickermaier, 2009).

While multimodal perception is hypothesized to contribute towards robustness in perception (Ernst & Bühlhoff, 2004), it is also documented to be the driving mechanism underlying many perceptual ‘illusions’ including spatial ventriloquism (e.g. Warren, Welch, & McCarthy, 1981), auditory driving (e.g., Adrian, 1934; Livanov & Poliakov, 1945), as well as the McGurk effect (Harry McGurk & John Macdonald, 1976). Interestingly, understanding the phenomena underlying such ‘illusions’ have also helped to illuminate the potential of multisensory perception as a mechanism in which interventions may capitalize upon to exact potential savings in energy consumption. For instance, energy may be saved by using multimodal perception to influence and improve thermal perception and comfort under stable and efficient room temperatures. In particular, multimodal visual activation of thermic concepts is proposed to be achievable via a widespread and long-standing psychological association known as the ‘hue-heat hypothesis’ (HHH). Formulated almost a century ago, the HHH paradigm posits that colours of longer wavelengths (i.e., predominantly of the red end of the wavelength spectrum) are associated with concepts of ‘warmth’, evoking congruent sensory perceptions, while shorter wavelengths (i.e., blue end of the spectrum) are associated with perceptions of ‘coolness’ (Heijs & Stringer, 1988; Mogensen & English, 1926).

Evidence supporting the HHH paradigm have been reported in recent studies; for instance, in one study exploring the effects of coloured LED lights in a light laboratory, participants’ assessment of the ambient room temperature was observed to be significantly warmer when under ‘warm’ yellow lighting than ‘cool’ blue lighting conditions (Winzen, Albers, & Marggraf-Micheel, 2014). The same participants also reported feeling more alert and

perceived air quality to be better under blue light conditions. Subsequent results of a study by the same authors in a realistic air-craft cabin environment were also found to be consistent with their previous findings and the HHH (Albers, Maier, & Marggraf-Micheel, 2015). In another study involving a climate chamber and two coloured hues of light (i.e., warm light/2700K, and cool light/6500K), the findings similarly reported an association between self-reported scores of thermal comfort with illumination colour (Huebner et al., 2016). Notably, the same study also observed behavioural cues that were taken to be an indication of thermal discomfort (e.g., changes in clothing levels) to be in a direction consistent with the HHH paradigm.

Other observations of HHH-congruent behavioural cues were also reported in another study where cold-induced shivering was found to be relatively higher for participants under the cooler (5800K) light compared to under the warmer (2700K) light condition (te Kulve, Schellen, Schlangen, & van Marken Lichtenbelt, 2016). In a more recent study, experimental findings revealed the extent of HHH-congruent effects induced by illumination colour temperatures to be such that actual room temperatures could be potentially altered without actually varying the subjective thermal perception of the subjects (Golasi, Salata, Vollaro, & Peña-García, 2019).

Notwithstanding the aforementioned evidence in favour of the HHH phenomenon, the effectiveness of illumination-based colour temperatures in influencing thermal perception within the literature has not always been consistent, with multiple research findings that conflict with the HHH instead (Candas & Dufour, 2005; Ho, Iwai, Yoshikawa, Watanabe, & Nishida, 2014). For instance, in one recent study investigating the potential use of the HHH in an indoor workplace setting, no evidence consistent with the HHH was reported across illumination temperature conditions of 2700K (i.e., warmer, yellowish-white), 4000K (i.e. neutral, white) or 6200K (i.e., cooler, bluish-white) – only that subjects felt thermally more

comfortable in an indoor workplace under the 4000K lighting temperature (Baniya, Tetri, Virtanen, & Halonen, 2018).

Such inconsistencies in empirical evidence of the HHH phenomenon are not completely unexpected, however, as a large number of studies do not appear to account for the effects of circadian rhythms (e.g. Baniya et al., 2018; Golasi et al., 2019; Ho et al., 2014; Winzen et al., 2014) despite their well-documented role in thermoregulation and ocular light sensitivity (Lucas et al., 2014; Sahin & Figueiro, 2013). Even for studies that did employ different time of the day sessions, the majority did not specifically analyse for circadian effects on thermal comfort outcomes (Albers et al., 2015; H. Wang, Liu, Hu, & Liu, 2018).

Exceptions include two recent studies. The first one of which found evidence of circadian influences on HHH-mediated effects in thermal comfort responses and concluded that the significant effects of coloured light could only be observed during “transitional phases” of the circadian rhythm (morning and evening) (Chinazzo, Wienold, & Andersen, 2018). The second study while finding support for the HHH, was nevertheless dismissive of the observed effects on the circadian rhythm – citing overly high illuminance of the lights used in the study as reason to be sceptical of circadian-related effects in their findings (Huebner et al., 2016). While informative, the first study was noted to have employed ‘glazed’ daylight (coloured by neutral, orange and blue filters applied onto windows) as their choice of light source, while both studies had only examined populations within a temperate climate context. Notwithstanding the small number of studies to draw from, the aforementioned factors also make it difficult to generalize the findings across other contexts (such as under artificial lighting, or on populations with different thermal perception requirements such as physiological adaptations to their respective climates).

4.1.4 Thermal Perception, The Circadian Rhythm and Light

Thermal perception in general refers to the sensation and perception of temperature; the perception of distinct temperature differences inferred from heat flux (i.e. the rate of energy transfer through a given surface) (Gidik, Bedek, & Dupont, 2016). With regards to thermal comfort – defined by the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) as the “condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation” (ASHRAE, 2013) – two theoretical approaches dominate discussion in the literature: the heat balance/predictive model of thermal comfort, as well as the adaptive model of thermal comfort (G. S. Brager & de Dear, 1998; Parsons, 2014).

In the heat balance model, six factors: ambient air temperature, mean radiant temperature, relative humidity, air velocity, metabolic rate and clothing level, are used to predict occupants’ overall satisfaction with the thermal environment as expressed by the Predicted Mean Vote (PMV) (Fanger, 1970). However, as many studies found individuals to be satisfied with thermal conditions beyond the range of predictions by the PMV, the development of alternative models of thermal comfort (adaptive models) appeared in order to factor in other drivers of importance (such as previous and current climatic experiences) that were beyond the considerations of the original heat balance model (Nicol & Humphreys, 1973). While both models have been applied to explain thermal perception, neither approaches have been overly successful; either failing to account for physiological or psychological adaptive mechanisms, or integrate findings from other disciplines (e.g., social sciences, engineering, health studies) (Schweiker, Huebner, Kingma, Kramer, & Pallubinsky, 2018). Reviews of the literature have also noted low predictive performances of between 30 to 50% of individual thermal sensation votes (Schweiker & Wagner, 2017).

Given the complexity of thermal perception, investigative studies have been growing across a broad variety of disciplines. The results of these efforts have led to multiple drivers of thermal comfort to be documented, such as physiological (e.g., age, gender, body composition, fitness, metabolism, and physiological adaptation due to temperature acclimation and circadian/diurnal rhythm) and psychological factors (Schweiker et al., 2018; Shipworth, Huebner, Schweiker, & Kingma, 2016). Specifically, the measure of thermal sensation, defined as the conscious feeling commonly graded into the categories cold, neutral and hot, is used to refer to answers obtained on a question asking specifically for a judgement of existing thermal conditions (warm, neutral or cold), while the measure of thermal comfort, defined as the condition of mind that expresses satisfaction with the thermal environment, is used to refer to answers obtained on a question asking specifically for an affective judgement of the experienced thermal environment (comfortable and uncomfortable) (ASHRAE, 2013). For thermal preference, this aspect is defined as favouring one condition above another, with response on the measure used within this thesis to denote the direction of an individuals' ideal thermal environment conditions.

For thermal acceptability and tolerance, the conceptual definitions are noted to be relatively broadest in meaning, generally interpreted as what the occupant is agreeable to or approves of (Brager, Fountain, Benton, Arens, & Bauman, 1993). While it may seem similar to thermal comfort, these measures are distinct, with subjective interpretation of what is acceptable and tolerable contingent on an individuals' context and/or preferences; for instance, one might find "slightly uncomfortable" to be acceptable and tolerable, while these definitions of what constitutes acceptable and tolerable may then be more narrowly or broadly defined depending on the person. Moreover, standardized ASHRAE scales for thermal perception have employed different survey questions to describe and capture different aspects of thermal perception, such as thermal sensation, thermal preference, thermal dissatisfaction, and thermal

comfort (Schweiker et al., 2018). A review of standardized survey questions designed to capture these aspects has also suggested distinct estimates to result for each question, supporting the notion that the scale measured the aforementioned concepts (Brager et al., 1993).

As previously mentioned, a potential gap within existing empirical studies of the HHH phenomenon may be due to a lack of consideration for some of such factors; in particular, the circadian/diurnal rhythm. Defined as rhythmic changes in physiological processes, the circadian rhythm is thought to essentially enable organisms to optimize their activities and metabolism via a variety of necessary arrangements as a pre-emptive response to upcoming changes in their environment conditions (Froy & Miskin, 2007).

The periodicity of such rhythms – defined as the time elapsed for a complete oscillation in circadian mechanism – is approximately the length of 24 hours (Cermakian & Boivin, 2003; Güldür & Otlı, 2017) and is thought to be a result of entraining of the circadian clock via external cues (Duez & Staels, 2008; Johnston, Frost, & Otway, 2009; Langmesser & Albrecht, 2006; Reilly, Westgate, & FitzGerald, 2007; Yang et al., 2006). In humans, the circadian rhythm is established to be strongly associated with core body temperature variations across the day (i.e. peaks in the late afternoon/early evening, and troughs in the morning/night) (e.g., Figueiro, 2013). Critically, the effects of circadian-related changes over the course of the day (phases) are posited to extend to thermal perception as well, with empirical evidence of significant impact on comfort temperatures such as higher preferences for ambient temperatures in the afternoon when core body temperature is typically at its highest (Karyono, 2000; Wagner et al., 2007; Z. Wang et al., 2018).

While the human circadian rhythm is noted to be highly susceptible to influence by a variety of environmental cues, of importance is the effects of ocular light which is reported to play a significant role in the functioning of circadian rhythms (Cajochen et al., 2005; Tähkämö,

Partonen, & Pesonen, 2019), in addition to being a key pathway in which the HHH intervention strategy is based upon. For instance, a large number of existing studies within the literature have demonstrated that exposure to even single pulses of bright light is capable of generating modest shifts (both advance and delay) to the different circadian phases (phase shifting) (Burešová, Dvořáková, Zvolsky, & Illnerová, 1991; Dawson & Campbell, 1991; Honma, Hashimoto, Endo, & Honma, 1997; Laakso, Hättönen, Stenberg, Alila, & Smith, 1993; Parry et al., 1997; Samková, Vondrašová, Hájek, & Illnerová, 1997; Shanahan, Kronauer, Duffy, Williams, & Czeisler, 1999; Zeitzer, Dijk, Kronauer, Brown, & Czeisler, 2000). Other studies have indicated circadian sensitivity to light stimuli to be phase dependent, with high sensitivity to light during biological night – the time when the circadian clock promotes sleep (Allan & Czeisler, 1994; Czeisler et al., 1989; Erren, Groß, & Fritschi, 2017; Jewett et al., 1997). Moreover, it is also reported that the exposure to light at different times of a phase leads to varying directions in the resulting phase shifts, such that exposure in the late biological day/early biological night was typically found to produce phase delay shifts, while exposure in the late biological night/early biological day resulted in phase advance shifts. In experiments to test phase shift with a 2-cycle stimulus, it was also revealed that reductions in amplitude of core body temperature and cortisol rhythms could be achieved using the aforementioned light stimulus type (Jewett, Kronauer, & Czeisler, 1991).

Critically, the wavelength of illuminance is also reported to play a role in impacting the human circadian system. For instance, phase shifting and melatonin suppression were reported to be significantly greater in subjects exposed to 460 nm light (bluer end of the light spectrum/'cool') relative to 555 nm light (redder end of the light spectrum/'warm') (Lockley, Brainard, & Czeisler, 2003a). Moreover, the subjects exposed to 460 nm light were generally more aroused, rating themselves as being significantly more alert, had faster reaction times, fewer lapses of attention, and displayed less EEG delta power and more EEG high alpha power

(Lockley et al., 2006) – reactions which one would associate with increased metabolic rates and potentially warmer thermal sensations. Likewise, exposure to light at 6500K (predominantly of shorter wavelength lights/’cool’) was found to be generally more arousing, leading to differences in cognitive performance such as significantly faster reaction times in tasks associated with sustained attention, relative to light at 2500K and 3000K (predominantly of longer wavelengths/’warm’), but not for tasks that were associated with executive function (Chellappa et al., 2011). Although these effects may appear to be contradictory to those posited by the HHH, it is noted by Chinazzo et al. (2018) that despite observing reductions in skin temperatures under exposure to orange ‘glazed’ lighting, such effects may not be pronounced enough to suppress the effects of coloured lighting on thermal comfort (Chinazzo et al., 2018).

Thus, with potentially profound effects on thermoregulation and perception, it is important that current research efforts on the use of multimodal applications of coloured lighting comprehend and address the effects on human physiology and the circadian rhythm.

4.1.5 Rationale and Aims

In summary, visual colour perception utilized to improve thermal comfort via the multimodal HHH phenomenon may be a promising energy conservation tool. However, a review of the empirical evidence available literature has also revealed conflicting findings. One potential issue may be due to the lack of consideration of the human circadian rhythm – physiologically endogenous (but exogenously modulated) oscillations which have been established in other disciplines to be highly relevant for thermoregulation and sensitivity to ocular light. Specifically, while the HHH posits ‘cooler’ (blueish) lighting to induce colder thermal perception relative to ‘warmer’ (reddish or yellowish) lighting, prior research on circadian effects has suggested potential contradictory effects instead on physiological responses. Moreover, majority of the existing literature for HHH-based thermal perception strategies have only been examined from a temperate climate context, leaving the effectiveness

of such potential interventions unclear among populations with distinctly different adaptations (i.e., acclimation).

To address these gaps within the literature, the current study aims to investigate the viability of an HHH-based strategy to influence thermal comfort in the context of a tropical climate (Singapore), taking the potential interaction effects with the circadian rhythm into account. Physiological measures were also monitored via wearable sensor technology in all experimental trials for thermoregulatory changes. These personal physiological monitoring devices were chosen in light of advancements in wearable sensor technology, where physiological signals such as skin temperature can now be captured with much relative ease and accuracy, (Li, Zhang, Zhao, & Liang, 2018; Nakayama, Suzuki, & Kameyama, 2009; Sugimoto, 2013; D. Wang, Zhang, Arens, & Huizenga, 2007). Moreover, in multiple studies, the skin temperature of the wrist was also found to be highly representative and accurate for thermal sensation estimation (Choi & Loftness, 2012; Choi & Yeom, 2017; Sim et al., 2016).

To guide the following investigations, several hypotheses to be tested in this study and their respective rationales are outlined below:

- To determine if lighting temperature does influence circadian processes, measures of skin temperatures (a physiological indicator of circadian processes) were analysed at different time periods of the day, across the range of room temperature conditions. As mentioned in prior studies (Chellappa et al., 2011; Lockley, Brainard, & Czeisler, 2003b; Lockley et al., 2006), the use of blueish (cool) lighting supposedly induces circadian effects in individuals that are associated with arousal; thus, warmer body temperatures should be expected. Moreover, the effects of coloured lighting should only be observed during “transitional phases” of the circadian rhythm (morning and evening).

- **H1.1:** Relatively higher skin temperature is predicted to be associated with blueish lighting than reddish/yellowish lighting.
- **H1.2:** The effect of coloured artificial lighting on skin temperature is predicted to be less pronounced in later time of the day sessions (e.g., late afternoon), relative to earlier time of the day sessions (e.g., morning).
- Next, to evaluate the effects of lighting on different aspects of thermal perception, standardized multiple measures of thermal perception (i.e., ASHRAE) were employed in the current study. Thus, we hypothesize:
 - **H2.1:** Scores on measures of thermal perception are predicted to differ significantly between lighting conditions (cool/warm).
 - **H2.2:** The effect of lighting temperature conditions on thermal perception is predicted to be less pronounced in later time of the day sessions (e.g., late afternoon), relative to earlier time of the day sessions (e.g., morning).

4.2 Design and Methodology

4.2.1 Participants

A total of 170 participants (84 females; mean age = 22.57 years, range = 21 – 32, $SD = 1.59$) were recruited for this study. The study design employed a mixed-design with the following parameters of interest: lighting-temperature (5600K/cool or 2700K/warm), air-temperature (22 to 27 °C), as well as time of day (10 am, 1 pm, 3 pm). No significant differences between the two illumination conditions were observed (see *appendix D*). The study was approved by the Nanyang Technological University Institutional Review Board and all procedures were performed according to guidelines.

Power analysis was conducted using the power analysis calculator from (Judd et al., 2017). With an estimated effect size of approximately 0.4 (Brysbaert, 2019) and expected power of 0.8, the minimum number of participants needed to power the study is 51.3. Using

the same model, the power of the current study in a reverse analysis is 0.917, which is above the recommended level of 0.8 (Brysbaert, 2019; Judd et al., 2017).

4.2.2 Experimental setup and equipment

The location of the experiment was a purpose-made, enclosed, windowless laboratory within the university campus. The laboratory interior was modelled to resemble a typical ‘office space’, which had 8 desks and desktop computers positioned all around the room evenly. Each of the desks had a desktop monitor of the same build and make, mouse and keyboard, all connected to a CPU. Each of the desks and office chairs was positioned to face a blank wall with minimal variations in illumination, temperature and wind velocity.

4.2.3 Lighting-temperature & Air-temperature

The lighting employed in the current study involved the use of a ceiling LED-based lighting system that was fully tuneable in colour temperatures (Figure 16). Calibration of the colour/hue of the illumination source was done first by measuring the correlated colour temperature (CCT) in degrees Kelvin (K) (Borbély, Sámson, & Schanda, 2001) using a spectrophotometer (*Konica Minolta illuminance spectrophotometer cl-500a*).

Figure 16. Image of the laboratory from either ends of the room under 2700K (left), or 5200K (right), illumination setting.

In the current study, exposure to either of two illumination settings: 2700K (yellow-reddish; called “warm” hereafter) or 5600K (white-blueish; called “cool” hereafter) was done between-participants while air temperature exposure was done within-participants. Measurement readings of illuminance and CCT showed average values of 1208 lux and 2715K for the warm lighting condition, while average values of 1209.9 lux and 5643K were found for the cool lighting condition. Differences in illuminance between both settings (1.9 lux) were lesser than that reported in previous literature (Huebner et al., 2016) – and less than one noticeable difference, according to Weber fractions (Griebel & Schmid, 1997).

Thermal parameters such as air-temperature and air velocity within the room were controlled via an air-conditioning thermostat and two ventilation fans. Additional recordings and monitoring of temperature conditions across the duration of each experimental session were taken with personal wearable devices allocated to each participant, as well as via a digital thermometer/ hygrometer unit (*UNI-T UT333BT*). Temperature settings employed in the study involve a range of temperatures between 22 to 27 degree Celsius ($^{\circ}C$), which are commonly encountered in a typical enclosed space in an urban building environment with regards to a tropical climate context.

4.2.4 Physiological data recording

Physiological data were recorded using the Microsoft Band 2 © (MB2) – a commercially available wearable sensor device that has been employed within previous literature. Due to the technology in personal wearable sensor devices being a relative development, there is currently only a small but growing number of empirical studies that have examined the validity, reliability and potential functionality of such devices (Morelli, Bartoloni, Colombo, Plans, & Clifton, 2018; Stahl, An, Dinkel, Noble, & Lee, 2016; Tophøj, Petersen, Sæbye, Baad-Hansen, & Wagner, 2018) such as in the field of healthcare (i.e., Majumder, Mondal, & Deen, 2017). As many manufacturers of such commercially available wearable devices do not openly

disclose relevant software algorithms and/or data validation processes due to propriety reasons, the use of the MB2 in the current study was done using a custom software application developed independently of the original software (W. Zhang, Hu, & Wen, 2018). In addition to being compatible with multiple operating systems (i.e. Android, iOS, Microsoft), comparable sensor quality and comprehensiveness of its functions, the MB2 provides easy access to data through its API relative to some of the other commercially available options (de Arriba-Pérez, Caeiro-Rodríguez, & Santos-Gago, 2016).

4.2.5 Procedure

To minimize variation, participants were given instructions via email on a dress code (i.e., T-shirt, long pants and covered shoes) for the experiment one day prior to their scheduled experiment session. Actual clothing (and any deviations) worn by participants for the experiment were recorded before, during, and after the experiment (Schiavon, Hoyt, & Piccioli, 2014). No significant differences in participant clothing level and background demographics were found across conditions (*appendix D*).

On arrival, participants were subject to a preparatory session of approximately 20 minutes in an enclosed, windowless area, with consistent artificial lighting provided by ceiling LED lights located just outside the experimental laboratory. The preparatory session served to ensure that all participants had adapted to similar activity levels, as well as thermal and illumination conditions before testing in order to reduce variability in pre-experimental state. Participants were first requested to read an introduction and instruction sheet before continuing. Consent forms were also given to participants to sign, after which a briefing was conducted using a standardized script on how to wear and operate the personal wearable device (MB2), with instructions given to calibrate the device according to their personal physiology (i.e., height, weight, age, gender). The study objective was presented as a generic investigation of

human physiological and psychological states in a built office space with no specific mention or emphasis on lighting or air temperature as the variables of focus.

Subsequently, participants were led into the room one at a time and were randomly assigned to be seated at one of the available desks. During the experiment, participants remained seated on the office chairs provided. In between measurements, participants were allowed to freely select and engage in a range of activities of their choice (i.e., studying, surfing the net, or reading), barring communicating directly to other participants, changing seating and/or desk positions, or engaging in any type of physical activity that might stimulate and alter their own or others' physiological states. In total, each experimental session lasted approximately 2 hours from the onset up until the final measurement had been submitted at 10am, 1pm, or 3pm each day and participants were not tested for multiple sessions in a given day.

4.2.6 *Outcome Measures*

Participants were periodically given an online survey (see *appendix D*) presented on their respective desktop computers at regular intervals of 10 minutes. In addition to physiological data (i.e., skin temperature), environmental data recordings (i.e., air temperature, air velocity) of each individual collected via the personal wearable devices was also conducted concurrently with the surveys at similar 10-minute intervals. For the online survey, the items corresponded to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard scales for thermal perception (ISO 10551:1995). Each item measured for a different, but related aspect of thermal perception (i.e., sensation, preference, comfort and dissatisfaction) (Table 6). In particular, the survey items assessed participants' subjective thermal perception (e.g., thermal sensation), present affective assessment of thermal conditions (e.g., thermal discomfort), future preference for thermal conditions, as well as judgement of local environment with separate items for personal acceptability and tolerance. The survey also

included two additional items measuring for existing perception of illumination and air quality conditions; specifically, perceived brightness of illumination conditions (i.e., light quality) and air quality tolerance respectively.

Correlation analyses for within-participant measures of the survey indicate a limited degree of correlation between all questionnaire items (see *appendix D* for more information); however, one item pertaining to future preferences of thermal conditions was observed to not correlate significantly with any other items in the questionnaire including present thermal sensation and discomfort, suggesting a potential and problematic lack of convergent validity. As such, the item was excluded in the final analyses.

Table 6. Outcome measure items on thermal perception, preference, acceptance and bearability, as well as lighting and air quality perception items. Items no. 1 to 5 corresponded to ASHRAE standard scales for thermal comfort.

No.		Response scale						
		1	2	3	4	5	6	7
1	How are you feeling in this moment?	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
2	Do you find the current thermal conditions...?	Comfortable	Slightly uncomfortable	Uncomfortable	Very Uncomfortable	Extremely Uncomfortable		
3	How would you prefer to feel?	Much cooler	Cooler	Slightly cooler	Without change	Slightly warmer	Warmer	Much warmer
4	Taking into account your personal preference only, would you rather accept than reject this climatic environment?	Yes	No					
5	Is this environment, in your opinion...?	Perfectly bearable	Slightly difficult to bear	Fairly difficult to bear	Very difficult to bear	Unbearable		
6	How do you find the current	Extremely dim	Dim	Slightly dim	Comfortable	Slightly bright	Bright	Extremely bright

	lighting conditions?							
7	How do you find the air quality in this room?	Perfectly bearable	Slightly difficult to bear	Fairly difficult to bear	Very difficult to bear	Unbearable		

4.3 Data Analysis and Results

Excluding personal acceptability of local thermal environment, statistical analysis of each outcome variable was conducted using the linear mixed-effects model (LMM) method via *R* statistical software and ‘*lme4*’ (Bates et al., 2015). In addition to its flexibility with a wide variety of correlation patterns and unequal variances, the use of the LMM approach would also help simultaneously account for the fact that trials across certain experimental manipulations (i.e., temperature) were nested within-subjects (with multiple responses from the same person) while lighting conditions (i.e., cool and warm) and time of day sessions were between subjects. For LMM computation, the Maximum Likelihood estimation method was employed, followed by an ANOVA with Satterthwaite’s method through the ‘*lmerTest*’ statistical package (Giesbrecht & Burns, 1985; Hrong-Tai Fai & Cornelius, 1996; Kuznetsova et al., 2017) to approximate the significance of effects. Effect sizes were estimated using the “*MuMIn*” statistical package while post-hoc contrasts of interaction effects were conducted using ‘*emmeans*’ statistical package with Tukey’s adjustments (Lenth, 2019). For ratings of personal acceptability of local thermal environment which used a binary response scale, a generalized form of the linear-mixed effects model (GLMM) was employed to account for the binomial distribution of the data.

Each outcome variable’s corresponding LMM model was analysed using the following fixed factors: the time of day, lighting type (i.e., cool or warm) and the average air-temperature, along with the following co-variates: gender, BMI, age, metabolic rate, clothing level and random effects of participant ID (see *appendix D*). Full models involving interactions between

the fixed factors were statistically compared against corresponding null and reduced models via χ^2 tests and both Akaike information criterion (AIC) and Bayesian information criterion (BIC) comparisons. Results of statistical model selection indicate a lack of impact of the covariates on model fit values but they were maintained in the final models due to theoretical relevance. The final selected models consisting of fixed effects and random effects variables were observed to significantly improve against null models.

4.3.1 Control measures: Brightness, Air Quality Perception

An analysis of several control measures was first conducted to determine if the experimental manipulations had any confounding effect on the subjective perception of air quality and brightness. Results of the LMM analyses revealed no significant effect of lighting type (i.e., warm, cool) on perceived air quality with a conditional R^2 of .41. For perceived brightness, results of the LMM analyses also indicated no significant differences between lighting type (conditional R^2 is observed to be .65), except with the very specific exception of responses given at 3pm time of day under low temperature levels ($< 24^\circ\text{C}$), with cool lighting perceived to be significantly brighter than warm lighting ($t = 2.00$, $df = 206$, $p = .047$). None of the subsequent results reported below was related to that specific period. Overall, the experimental manipulations did not appear to affect perceived air quality and perceived brightness.

4.3.2 Skin and Air temperature, Thermal sensation

A comparison of participants' skin temperature on a range of ambient air temperatures under different lighting conditions and time of the day sessions was conducted to investigate the role of the circadian rhythm in an ocular light-based intervention to influence thermal perception. The results of the analyses revealed a significant effect of lighting temperature on

participants' recorded skin temperatures, qualified by a 3-way interaction with the time of day and air temperature ($F_{2, 1801.83} = 27.17, p < .001$) with a conditional R^2 of .75 (Table 7).

Mean skin temperatures in both lighting conditions were found to be positively associated with air temperature (Figure 17). Post hoc comparisons were found to be supportive of hypothesis *H1.1*, revealing skin temperatures of participants to be significantly higher under cool lighting conditions relative to warm lighting conditions at 10 am ($t = 2.063, df = 242, p = .040$) at mid-to-low air temperatures ($< 25\text{ }^{\circ}\text{C}$). The analyses also revealed significant differences in the rate of change in skin temperatures between lighting conditions during the 10 am sessions, such that skin temperature changed at a significantly higher rate under warm lighting than cool lighting conditions across air temperatures ($t = -3.93, df = 1756, p < .001$).

Table 7. Type III ANOVA with Satterthwaite's method of LMM Skin Temp by Air Temp.

Variable	MS	F	P
clothing_level	1.20	2.66	0.103
BMI	0.56	1.24	0.267
Age	0.14	0.31	0.581
Gender	4.80	10.59	0.001**
TimeOfDay	18.16	40.10	< 0.001***
Lighttype	0.92	2.03	0.15
average_air_temperature	811.15	1790.95	< 0.001***
TempType	19.45	42.94	< 0.001***
Metabolic_rate	0.15	0.33	0.57
TimeOfDay:Lighttype	13.06	28.85	< 0.001***
TimeOfDay:average_air_temperature	18.51	40.86	< 0.001***
Lighttype:average_air_temperature	0.77	1.70	0.192
TimeOfDay:Lighttype:average_air_temperature	12.31	27.17	< 0.001***

* $p < .05$, ** $p < .01$, *** $p < .001$.

In contrast, at 1 pm a significantly higher rate of change in participants' mean skin temperature under cool lighting than for those under warm lighting was observed ($t = 6.27, df = 1853, p < .001$). Post-hoc pairwise comparisons subsequently revealed skin temperatures at

1 pm to be significantly higher under warm lighting than under cool lighting ($t = -3.176$, $df = 199$, $p < .01$) at mid-to-low air temperatures (< 26 °C). No evidence of significant skin temperature differences between lighting conditions was observed for 3 pm time of day sessions, congruent with predictions made in hypothesis *H1.2*.

Figure 17. Graph of LMM fitted values of skin temperature (y-axis) against average air temperature (x-axis), grouped by lighting temperature and time of day sessions. Bands denote the S.E

Unlike skin temperatures, subjective measures of thermic perception (i.e., thermal sensation) may not always reflect objective changes in air temperatures as straightforward or linearly. Hence, employing subjective thermal sensation ratings in lieu of air temperatures, similar analyses were done to elucidate if lighting effects on mean skin temperatures were translated across discernible levels of thermic experience/perception and whether said effects were subject to influences by the circadian rhythm.

The findings revealed that similar to the findings with air temperatures, there was a significant effect of lighting temperature on skin temperatures qualified by a significant 3-way interaction with both the time of day and thermal sensation ratings ($F_{2, 1823.45} = 4.88, p < .01$; conditional $R^2 = .59$). Likewise, skin temperatures and thermal sensation scores were observed to be positively associated (Figure 18), such that subjectively ‘hotter’ mean thermal sensation ratings corresponded with skin temperature increases regardless of lighting conditions.

Moreover, comparisons of the rate of change in skin temperature were such that cool lighting was found to be associated with a higher rate of change than in warm lighting at 1 pm ($t = 3.08, df = 1849, p < .01$), similar to previous air temperature results reported above. Pairwise comparisons of mean skin temperatures also revealed those in cool lighting conditions to be significantly lower than mean skin temperatures at warm lighting conditions, at ‘slightly cool’ to ‘cold’ thermal sensation ratings (< 4) during 1 pm sessions ($t = -2.87, df = 214, p < .01$), similar to analyses with air temperatures as well. Differences in mean and the rate of change of skin temperatures between lighting conditions were also not found at 3 pm time of day sessions, similar to the previous findings. In contrast to the previous analyses, no significant differences in the rate of change of thermal sensation ratings were observed between lighting conditions for 10 am and 3 pm sessions.

Figure 18. Graph of LMM fitted values of thermal sensation ratings (y-axis) against skin temperatures (x-axis), grouped by lighting temperature and time of day sessions. Bands denote S.E.

4.3.3 Thermal Discomfort

To understand the potential effects of lighting on affective evaluations of thermal conditions, the current study analysed thermal discomfort ratings with thermal sensation ratings in lieu of air temperatures, along with lighting temperature, the time of day, and potential interaction effects. An LMM analysis revealed a significant 3-way interaction between lighting, time of day, and thermal sensation ($F_{2,1728.84} = 4.89, p < .01$) with a conditional R^2 of .41. The relationship between thermal sensation and thermal discomfort scores were as such that higher sensations of warmth corresponded with increased thermal discomfort (Figure 19).

Figure 19. Graph of LMM fitted values of thermal discomfort (y-axis) against thermal sensation ratings (x-axis), grouped by lighting temperature and time of day sessions. Bands denote S.E.

Congruent with predictions made in hypothesis *H2.1*, evidence of differences between lighting conditions were observed for measures of thermal discomfort; specifically, post-hoc analyses subsequently revealed thermal discomfort ratings to increase at a significantly higher rate as subjective assessments of thermal conditions grow warmer when under warm lighting than cool lighting during 1 pm sessions ($t = -2.634$, $df = 1791$, $p < .01$). Pairwise comparisons of estimated means also revealed a significantly higher mean discomfort rating in warm lighting than in cool lighting, at ‘neutral’ to ‘hot thermal sensation ratings ($4 \leq$) during 1 pm time of day sessions ($t = -2.14$, $df = 195$, $p = .034$). Conversely, no significant differences between lighting conditions were found for both 10 am and 3 pm time of day sessions, in contrast to predictions for hypothesis *H2.2*.

Thus, the findings suggest that while thermal discomfort generally increases with hotter perceived temperatures (i.e., thermal sensation), exposure to cool lighting appears to improve the level of perceived thermal comfort relative to warm lighting – an observation congruent with the HHH. Moreover, observations of the aforementioned ‘hue-heat’ effects on thermal comfort were found to be dependent on the circadian rhythm, manifesting only at 1 pm, but not at either 10 am or 3 pm.

4.3.4 Personal Tolerance

For participants’ subjective ratings of tolerability of thermal conditions (personal tolerance), an LMM analysis was conducted with the following variables: lighting, time of day, and thermal sensation. Results revealed a significant 3-way interaction between lighting, time of day and thermal sensation ($F_{2, 1771.76} = 3.11, p = .045$), with a conditional R^2 of .43. The association between thermal sensation and personal tolerance ratings were such that ratings of ‘less’ tolerance were associated with subjectively hotter sensation scores (Figure 20). Subsequent post-hoc analyses revealed an effect of lighting condition on the rate of change of personal tolerance ratings; that as thermal sensation ratings become hotter, personal tolerance decreased faster when under warm lighting relative to cool lighting conditions at 1 pm ($t = -2.998, df = 1826, p < .01$). Furthermore, pairwise comparisons indicate tolerance ratings to be significantly ‘less’ tolerable for participants under warm lighting relative to cool lighting, at ‘slightly warm’ to ‘hot’ thermal sensation ratings (4 <), at both 10 am ($t = -2.09, df = 263, p = .038$) and 1 pm time of day sessions ($t = -2.39, df = 288, p = .02$). No such differences were noted at 3 pm. These observations appear to be congruent with hypothesis H2.2.

Figure 20. Graph of LMM fitted values of personal tolerance ratings (y-axis) against thermal sensation ratings (x-axis), grouped by lighting temperature and time of day sessions. Bands denote S.E.

4.3.5 Personal acceptability

To evaluate the effects of lighting, on participants' evaluation of personal acceptability of the existing thermal environment, a GLMM analysis was performed. Contrary to predictions made in both hypothesis *H2.1* and *H2.2*, the results revealed no significant effect of lighting conditions on participants' acceptance ratings (theoretical $R^2 = .55$; delta $R^2 = .40$).

4.4 Discussion

The current study aims to investigate specific gaps within the literature regarding the use of a multimodal HHH strategy as a non-informational intervention; specifically, on the role of the circadian rhythm in a coloured (artificial) lighting-based strategy to improve thermal perception within a tropical climate context.

The results of the current study found coloured lighting to have a significant impact on physiological circadian process and thermoregulation. In particular, significantly higher skin temperatures were observed under exposure to blueish cool light in the morning sessions – in line with previous research findings which suggested circadian mechanisms to be in play (Chellappa et al., 2011; Lockley et al., 2003a, 2006). These observations are also noted to be congruent with reports from previous studies, where increased core body temperature and heart rate were both noted to be ‘blue-shifted’ (i.e. trending towards cooler colour wavelengths), following the suppression of melatonin production – a phenomenon which typically occurs in the morning (Cajochen et al., 2005). In addition, the lack of significant differences in skin temperature between lighting conditions at late afternoon sessions also provides some support to the notion of increased susceptibility to illumination during different phases of the circadian rhythm.

However, while blueish light was associated with significantly higher skin temperatures during the morning, this effect appeared to be inversed during the middle of the day. Similar findings within the physiological literature have also suggested red light to be a stronger alerting stimulus in the afternoon (Sahin & Figueiro, 2013), potentially via alternative pathways that are independent of melatonin suppression. This is similar to previous findings of circadian-based differential sensitivities and responses to ocular light (Khalsa, Jewett, Cajochen, & Czeisler, 2003; Kozaki, Kubokawa, Taketomi, & Hatae, 2015), although the exact mechanisms are unclear.

Analyses with thermal sensation ratings revealed this thermal sensation aspect of thermal perception to be congruent with light-mediated differences in skin temperature during the middle of the day, but are decoupled in the mornings. Similar findings were also observed for thermal discomfort and personal tolerance of thermal conditions, but not for personal

acceptability of thermal conditions. Taken together, these findings suggest the interactions between circadian and coloured lighting on aspects of thermal perception to be complex.

Firstly, the multimodal influence of coloured lighting appears to affect most aspects of subjective thermal perception in the middle of the day, contrary to the hypothesized “transitional phases” such as morning and evening (Chinazzo et al., 2018). In particular, at midday sessions, we find that cool lighting was able to induce colder thermal sensation evaluations, which was evaluated more favourably (lower thermal discomfort and higher personal tolerance) relative to exposure to warm lighting.

In the mornings, the multimodal influence of coloured light appears to be less expansive on different aspects of thermal perception; with only personal tolerance to thermal conditions appearing to be relatively higher (better) with exposure to cool lighting relative to warm lighting. Moreover, as this relationship with skin temperatures appears to be inversed in comparison to midday – where higher tolerance is now noted to be associated with relatively higher skin temperatures under cool lighting, the findings suggest a shift in subjective thermal preferences that is circadian related. While previous findings have suggested circadian physiological thermoregulation responses to be contradictory with potential HHH illumination-based effects on thermal perception (Huebner et al., 2016), the current findings reveal empirical evidence suggesting the interaction between both to be complementary instead; with shifting preferences in thermal conditions maintaining a consistently more favourable (i.e., comfortable) HHH effect of cool lighting relative to warm lighting from morning to midday.

Interestingly, while no observable effects of lighting temperature for most measures were reported at 3 pm time of day session, lighting quality perception was found to differ for the same time of day session. In particular, brightness was rated to be subjectively higher under warm lighting than under cool lighting, despite both lighting conditions having similar

objective luminance levels, potentially alluding to lighting preference differences that are also circadian-mediated.

While the current findings indicate support for the HHH as well, there are some key factors of importance that have been highlighted in comparison with previous HHH studies. For instance, the type of light source (artificial lighting or daylight) may influence the sensitivity of different circadian phases to coloured light thermal perception effects, given similar comparisons in previous studies with animal models (Sharma, Chandrashekar, & Nongkynrih, 1997).

Another factor of interest may be differences in conditions and samples from different climate contexts. In particular, previous HHH studies on thermal perception have been primarily conducted on populations and conditions in temperate climates, subsequently observing that the use of lower correlated temperature lights (of predominantly longer wavelengths/ reddish or yellowish) to result in better thermal comfort (Chinazzo et al., 2018; Huebner et al., 2016). In contrast, the current study examined conditions and populations within a tropical climate context, such as expanding the previous range of temperatures studied (22 to 24°C) by another 3°C to accommodate typical conditions encountered locally. Conversely, the current study noted cool light to predominantly result in better thermal comfort assessments, even at previously studied temperatures. Thus, prior physiological adaptations (acclimation) are likely to play a key role in light-mediated intervention effects on thermal perception (of an HHH-based intervention).

Overall, the current findings indicate that HHH-based influences on thermal perception are subject to the different circadian phases, suggesting that some of the prior observations of ‘no effects’ of coloured lighting on thermal perception to potentially be a result of exposure during a non-optimal time of day. Thus, by factoring in considerations of the circadian rhythm, future studies may better understand and modulate thermal perception via coloured lighting,

reducing the variability and inconsistencies found in previous literature and avoiding erroneous conclusions.

While the findings of the current study indicate a significant role of the human circadian rhythm in HHH thermal comfort interventions, the full extent of potential impacts of prolonged coloured lighting exposures is unclear. For instance, the potential effects on the sleep/wake cycle and multiple cascading physiological processes present a probable cause for concern as shifts in circadian phases and activity may result in not just adverse physiological effects (such as cardiovascular diseases and cancer) (Blask et al., 2005; Elliott, 1998; Goldberg et al., 1990; Kozaki et al., 2015; Manfredini et al., 2005; Muller et al., 1985; Muller & Tofler, 1991; Stevens et al., 2007; Thosar, Butler, & Shea, 2018; Twidale, Taylor, Heddle, Ayres, & Tonkin, 1989; Willich, Goldberg, Maclure, Perriello, & Muller, 1992), but also have potential psychological (i.e., alertness) ramifications (Ahmad et al., 2020; James, Honn, Gaddameedhi, & Van Dongen, 2017; Karatsoreos, 2012; Salgado-Delgado, Tapia Osorio, Saderi, & Escobar, 2011).

Aside from chronobiological impacts, the colour composition of white light in LED lighting may also be a cause for concern, potentially delivering a much higher amount of blue and ultraviolet light emissions relative to other previous lighting sources (such as incandescent) (Behar-Cohen et al., 2011). Specifically, blue light has the highest photon energy in the visible spectrum, readily penetrating through the cornea and lens to reach the retina, potentially resulting in retinal damage (Boettner & Wolter, 1962; Zhao, Zhou, Tan, & Li, 2018) – a phenomenon known to ophthalmologists as the “blue light hazard” (Hatori et al., 2017).

Although data from animal and in-vitro studies have suggested blue light to be phototoxic (Ham, Mueller, & Sliney, 1976; Ueda, Nakanishi-Ueda, Yasuhara, Koide, & Dawson, 2009), the evidence for phototoxicity in our everyday life is still lacking (O’Hagan, Khazova, & Price, 2016), with none of the measurements of blue light from a range of light sources such as CFL and LED lamps, computer screens, tablet computers, laptops and smartphones assessed to

approach the blue light hazard exposure limits set by the International Commission on Non-ionizing Radiation Protection (ICNIRP), even for extended viewing times (*International Commission on Non-ionizing Radiation Protection*, 2013).

While reviews have not found evidence to support the use of short-wavelength filtering spectacle lenses for the general population to improve visual performance, delay myopia and conserve macular health (Lawrenson, Hull, & Downie, 2017; Zhao, Jiang, Yu, & Xu, 2017), interestingly, data from animal models and in children have instead suggested blue and violet light exposure to be beneficial, suppressing myopia progression in subjects (Torii et al., 2017; Wang, Zhou, Lu, & Chu, 2011).

Although it may still be too early to conclude the long-term effects of exposure to blue light on human health, LED lighting available in the market for domestic use may emit substantial levels of blue light, posing low to moderate phototoxic risks on the retina (depending on the levels of radiant flux, exposure distance and durations) (Behar-Cohen et al., 2011) - specifically for cold-white light that have a strong blue component. Thus, it is recommended that the use of LED cold-white light is avoided in places frequented by children (e.g. nurseries, schools) as the absorption spectrum of the lens is age-dependent (Kessel, Lundeman, Herbst, Andersen, & Larsen, 2010), and that manufacturers and integrators of such LED lighting conduct quality controls to ensure their products are within exposure limits such as those set by the ICNIRP.

Thus, it is recommended that more attention is given to the role of the circadian rhythm, as well as the long-term impacts in future applications of an HHH light-based energy saving intervention. Future studies may instead adopt a circadian-hue-heat hypothesis (cHHH): a modified and updated hue-heat theory which accounts for the implicit influence of circadian physiology and which may be subsequently expanded upon. Specifically, while the predictions of the cHHH would resemble the current iteration of the HHH (i.e., where warmer

lighting/colours would activate thermic concepts related to warmth and elicit changes to subjective thermal perception), it differs in that the psychological effects of colour are to be considered in the context of the human circadian phase (i.e., time of day periods). For instance, the implementation of cooler lighting may be focused upon the specific time of day periods where improvements to thermal comfort are optimal. Moreover, the use of the cHHH as a basis for formulating future research would help direct efforts to allow for more relevant data to help inform and optimize the implementation of said intervention strategies.

5 Discussion and Conclusions

5.1 Discussion and Conclusions

People are visual creatures and vision drives much of our experience of the world. As intuitive as vision may seem to be, the application of visual perception principles in the sustainability literature has been severely lacking. Rather, the literature has primarily focused upon sociopsychological approaches which while invaluable, does not necessarily translate into appropriate assumptions and implementation methodology with respect to the neurophysiological constraints of our visual perception and cognition systems. By addressing the unclear or heterogeneous assumptions regarding the use of different informational displays, to the use of vision and the environment to influence thermal comfort and behaviour, the current dissertation aims to address challenges in influencing sustainable behaviours from a visual perception and cognition approach.

Firstly, of the plethora of existing behavioural intervention strategies, information provision represents one of the most commonly utilized approaches. However, despite the predominantly visual nature of energy information feedback strategies, there is a lack of clarity and available data on the different aspects of visual information communication within the field itself. From the findings of both Study 1 and 2, it was found that although feedback information on utility consumption as given in a typical utility bill in Singapore was effective at drawing visual attention, information perception as measured via a judgment task was found to be distorted by non-relevant information. Moreover, spatial position was found to not be a significant factor influencing the judgements of either utility's efficiency (Study 2), indicating the longer fixations on AOI3 (water graph) than AOI 2 (electricity graph) to be likely due to other reasons aside from higher attentional salience arising from spatial positioning. One potential reason may be comprehension difficulty, where the differences in utility type and consumption characteristics (e.g., different physical units) may have played a part instead in

longer and more frequent gazes. Additionally, differences in prior assumptions such as semantical or conceptual understanding of the utilities might have resulted in differences between the visually similar information formats.

In addition to potential ramifications for behaviour and energy usage intervention outcomes (e.g., rebound effect, higher thresholds to act and/or lowered effectiveness of information messaging), findings from Study 1 and 2 suggest cognitive and perceptual factors when accessing information to have a significant influence on visual gaze behaviour and on judgement of information. Broadly, the findings of Study 1 and 2 suggest existing conventions of how different but related information is generally communicated in our daily lives to require more attention, with potential cognitive bias(es) present that could have significant implications on judgement and decision making. Taking this one step further, this implies that the way information is accessed might influence how sociopsychological drivers (such as motivation, knowledge, intention etc.) impact behaviour.

While the exact mechanisms are currently unclear, to decouple the potential impacts of visual information parameters from other drivers, future research will need to pay closer attention to how information is communicated, such as with more stringent adherence to consistency in visual parameters across different conditions (e.g., information type), and/or reporting the systematic characterization(s) of the cognitive and perceptual qualities of (different) information parameters employed. For instance, in studies evaluating differences between information types (e.g., ecological messages vs. socio-normative information), matching of the layout, form (e.g., graphical, pictorial, text, numbers, tables) and other visually distinct variables could help reduce variability. Additionally, evaluating the impacts of different visual parameters (on the way information is perceived and cognitively employed) would not only improve our understanding of hypothesized focal sociopsychological drivers

but also allow for more robust future implementations and more effective information provision strategies.

Notwithstanding characterizing visual information perception on other common formats of information provision, further empirical study of the mechanisms underlying information perception distortions could be conducted to better clarify and understand the drivers of the observed phenomenon. For instance, investigating each of the plausible associated biases underlying the observed distortion effects; whether they are driven by specific decision-making heuristics such as context effects (i.e., assimilation, contrast effects), recency effects, or both. Likewise, whether variations in task goals (e.g., judgments of efficiency for others, in the absence of existing socio-normative information, or of ‘sustainability’ rather than efficiency) may lead to qualitatively and quantitatively different outcomes. Future research may attempt to investigate how these biases may be offset (mitigating strategies for the perceptual distortion of visually communication information), such as by reducing the availability of contextual cues that may induce assimilation or contrast effects, which may also help implementation and intervention efforts.

Extending the findings of the previous two studies (i.e., that the visual perceptual system is an integral component of energy behaviour interventions, being not only relevant for information-based strategies, but also as a potential pathway for non-informational ones), Study 3 examines colour perception as a potential pathway to reduce energy consumed in space cooling. The current data adds supporting evidence for the use of the hue-heat hypothesis to influence thermal perception of the environment via multimodal mechanisms, while also addressing the lack of consideration for the role of physiological characteristics (e.g., the circadian rhythm) on thermal perception within the existing literature. Specifically, our findings indicate the HHH effects on thermal perception to be dependent on circadian shifts in thermal preferences and thermoregulatory changes, suggesting a need for the effects to be

considered within the context of the time of the day. Thus, autonomous intrinsic systems such as the circadian rhythm may account for why HHH effects work in some contexts and not in others, indicating a need to expand the existing theoretical conception of the hue-heat hypothesis for future research and applications work.

Overall, the results of the current dissertation suggest potential improvements and increased viability of ongoing and nascent interventions with the adoption of visual perception and cognition approaches. to be viable candidates for future implementation as a complementary set of interventions.

With regards to the limitations in the aforementioned research, it is acknowledged that the applications as described have not been associated with actual behavioural outcomes and subsequent testing in both laboratory and field deployments due to limitations on resources and time. As such, it is unclear if the current approach is able to realize significant improvements in energy consumption behaviours. For instance, the provision of information may not necessarily lead to behavioural changes as barriers stemming from structural (e.g., inefficient appliances, housing type) and contextual factors (e.g., household size, home ownership status) could plausibly prevent energy sustainability actions, reducing overall potential savings in energy.

Another potential limitation in Study 3 relates to post-hoc analyses of semantic relatedness; that cultural and territorial differences in language development (Schneider, 2003) could potentially influence the outcomes of the analyses. Specifically, that language varieties arising from varying idiosyncratic historical conditions, contact settings and other potential influences could result in polysemic differences, variations in the strengths of semantics links, or word frequency (Schneider, 2003). For instance, in places such as Australia and New Zealand, English is assessed by Schneider to have reached the fifth stage of development (a fully mature new variety of English with its own modes of pronunciation and patterns of use

that are free from dependence on external sources of orientation) (Schneider, 2003), given that the people there no longer reference British English for their norms. In contrast, Singapore English is classified as being in the fourth stage – characterized by endonormative stabilisation and the gradual adoption and acceptance of local norms (Brown, 1999; Cruz-Ferreira, Deterding, Brown, & Low, 2005; Tongue, 1974; Wee, 1998). While such differences may be impossible to avoid entirely in any corpus, their effects on aspects of semantic relatedness are currently unclear, which may hinder the interpretation of the current findings. Thus, it is recommended in future research to account for the potential effects of local language culture and developments, such as getting participants to rate the words to determine the actual semantic relatedness of the terms used.

For a coloured lighting and thermal perception intervention, potential gaps in knowledge include the association with actual thermal conditioning usage behaviour (i.e., thermostat adjustments arising from discomfort levels). Likewise, other obstacles may lie in being able to convince building and home owners to adopt the recommendations for lighting. For instance, the use of lighting often has aesthetic purposes and individuals may not wish to compromise on such an aspect of their environment. Other potential issues may be that control of the thermostat in certain built environments is just not accessible to the individual (e.g., central cooling or heating systems in offices or rental apartments). Likewise, due to the small number of existing empirical studies, there is still a great number of unknown variables surrounding the implementation of this intervention type, including the actual effects of coloured lighting on night-time circadian phases and resulting thermal perception.

Hence, in addition to recommendations for future work addressing the issues above, it is critical that the identification of alternative non-conflicting interventions can be developed to address a greater scope of energy behaviours that have a substantial impact (e.g., water heating).

5.2 Policy recommendations

Overall, insights garnered from the current findings could be useful for a broad number of stakeholders ranging from governments and policy makers, institutions and large companies, to individuals and society as a whole. Depending on the scenario, interventions or policies employing provision of information are highly advised to investigate and incorporate considerations of visual parameters and perception. For instance, imagery could be designed to communicate the distinctiveness or interrelationships of different resource or utility categories, such as having visually different types of representative charts or by increasing spatial separation (e.g., different pages) to minimize distractor information effects.

In contrast, the relationship between water and energy consumption in domestic contexts may conversely be emphasised in the provision of information (e.g., illustrations or graphical breakdowns) highlighting the average energy consumption and/or total energy composition of such activities (e.g., % of total energy spent on average to heat, purify or transport water). The saliency of certain information presentation formats such as graphical, pictorial or textual could also be capitalized upon to either help accentuate, or conversely reduce emphasis on certain types of information (e.g., pecuniary information) to optimize the efficiency of behavioural interventions, depending on the demographics, neighbourhood, or other sociocultural or contextual variables.

Moreover, apart from utilities billing, the visual communication and presentation of information provision strategies in other instances may also potentially be prone to exhibiting similar issues as characterized in the current study, notwithstanding other specific eccentricities. For instance, in other mediums of information provision such as in e-billing/online bills, it is important to consider not only the visual parameters covered within this study but also other parameters that may influence information cognition and perception,

such as in the visual navigation of information (e.g. scrolling) which may have additional variables of consideration (e.g., the length/distance of scrolling), the presence/use of interactable information displays and/or usage of animation. Similarly, other mediums of information provision such as utility or appliance smart displays may be regulated to provide considerations of such parameters and their resultant effects on individuals' perception of energy consumption and efficiency, attention, and even other factors such as trust.

For the findings of multimodal visual colour perception-based thermal perception and comfort intervention, the implications are broad, being relevant not just for future work involving the application of the multimodal HHH paradigm but also in other interventions involving multimodal integration of other sensory modalities, as well as in design considerations of both illumination and thermal conditions in a variety of indoor spaces including offices, workspaces, various recreational and educational facilities, within mass-transport vehicles such as aircraft cabins and trains, and/or other public spaces. The findings of the current study may also thereby be utilized to help institutions and policymakers select and employ appropriate market interventions, such as in encouraging the adoption of climate congruent illumination use (e.g. warmer lighting for temperate zones and cooler lighting for tropical zones) or even in civil engineering projects where applicable, ultimately to not only improve occupant comfort and reduce consumption in buildings and indoor environments but to also maintain or even improve occupant/workspace cognition and performance.

Beyond the visual processing and cognition principles applied within this current work, the findings have also suggested the notion that other multidisciplinary efforts may potentially be utilized in similar ways to influence perception and guide sustainability and/or other socio-beneficial objectives. Critically, any such future initiatives into influencing human behaviour should not only take into consideration the intrinsic characteristics of human perception and cognition but also account for potential physiological processes.

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APPENDIX A: SUPPLEMENTARY MATERIALS FOR EYE-TRACKING MEASURES

Table A1. Descriptive statistics of eye-tracking measures categorized by AOI.

AOI	Fixation Duration			Fixation Count
	Mean	SD	SE	(N)
1	542.75	412.75	84.25	24
2	1309.56	1227.07	123.95	98
3	2124.18	1491.17	144.84	106
4	553.00	361.81	57.94	39
5	588.51	439.12	64.05	47
6	704.36	657.13	124.19	28
7	241.50	177.54	56.14	10
8	261.65	179.03	43.42	17
9	631.15	563.52	89.10	40
10	671.35	591.90	79.81	55
11	788.31	912.25	135.99	45

APPENDIX B: SUPPLEMENTARY MATERIALS FOR SEMANTIC RELATEDNESS

Table B1. DESCRIPTIVE SUMMARY OF WORD RELATEDNESS METRICS.

No.	Metric	Descriptive summary
1	WUP	The Wu & Palmer (WUP) word similarity metric calculates semantic relatedness via considerations of the depths of both synsets within the WordNet taxonomies, along with the depth of the least common subsumer (LCS). The WUP formula is: $\text{Score} = 2 * \text{depth}(\text{LCS}) / (\text{depth}(s1) + \text{depth}(s2))$; where $0 < \text{Score} \leq 1$. A score of 1 occurs if the two input concepts are the same.
2	JCN	The Jiang & Conrath (JCN) measure was originally a distance metric which also employs the notion of information content (IC), albeit in the form of the conditional probability of encountering an instance of a child-synset, given an instance of a parent synset. The JCN formula is: $\text{Score} = 1 / \text{jcn_distance}$, where $\text{jcn_distance} = (\text{s1}) + \text{IC}(\text{s2}) - 2 * \text{IC}(\text{LCS}(\text{s1}, \text{s2}))$. *LCS = least common subsumer.
3	LCH	The Leacock Chordorow (LCH) measure relies on the length of the shortest path, specifically of two synsets, for the measure of both their similarity. The LCH formula is: $-\log(\text{length}(a, b) / (2 * D))$, where 'length' refers to the length of the shortest path between the two synsets (a, b) (using node-counting), while D refers to the maximum depth of the taxonomy.
4	LIN	Lin's measure of word semantic relatedness is similar to JCN with some small modifications. The formula is: $\text{Score} = 2 * \text{IC}(\text{LCS}(\text{s1}, \text{s2})) / (\text{IC}(\text{s1}) + \text{IC}(\text{s2}))$, where IC refers to information content, while LCS refers to the least common subsumer.
5	RES	The semantic similarity measure proposed by Resnik, defines the similarity between two synsets to be the information content (IC) of their lowest super-ordinate (most specific common subsumer). The RES formula is: $\text{Score} = \text{IC}(\text{LCS}(\text{s1}, \text{s2}))$, where IC is information content, LCS is least common subsumer, s1 and s2 refers to the two concepts of interest.
6	PATH	This measure computes the semantic relatedness of word senses by counting the number of nodes along the shortest path between the senses in the 'IS-A' (inheritance/subsumption relationship between abstractions in object-oriented programming) of hierarchies of WordNet. $\text{PATH}(\text{s1}, \text{s2}) = 1 / \text{path_length}(\text{s1}, \text{s2})$.
7	LESK	The LESK measure proposes that the semantic relatedness of two words of interest is proportional, according to the extent of overlaps of their respective dictionary definitions. This measure employed is based on an adapted version from Banerjee and Pedersen (2002), utilizing WordNet as the dictionary for the word definitions, rather than using a standard dictionary. Computational cost is relatively high due to combinations of linked synsets to explore definitions, and need to process these texts. Formula: $\text{Score} = \text{sum}_{\{s1' \text{ in linked}(s1), s2' \text{ in linked}(s2)\}} (\text{overlap}(s1'.\text{definition}, s2'.\text{definition}))$.
8	HSO	This relatedness measure is based on the concept that two lexicalized concepts are semantically more related should their WordNet synsets be connected by a path that isn't too long, and that the path in question "does not change direction too often". Computational cost for this metric of relatedness is relatively high, owing that recursive search is completed on subtrees within the horizontal, upward and downward directions. Formula: $\text{Score} = C - \text{len}(\text{s1}, \text{s2}) - k * \text{turns}(\text{s1}, \text{s2})$, where C and k are constants defined empirically (see Hirst & St-Onge, 1998), len is the length of the shortest path between s1 and s2 considering all relations and the patterns, while turns is the number of changes of direction in this path

Table B2. Word relatedness measures of "water" and "electricity" with the word "efficiency".

Word definitions: (1) water#1 - (n) a binary compound that occurs at room temperature as a clear colourless odourless tasteless liquid; freezes into ice below 0 degrees centigrade and boils above 100 degrees centigrade; widely used as a solvent. (2) water#2 - (n) water supply/system; a facility that provides a source of water; "the town debated the purification of the water supply". (3) electricity#1 - (n) a physical phenomenon associated with stationary or moving electrons and protons. (4) electricity#2 - (n) electrical energy; energy made available by the flow of electric charge through a conductor; "they built a car that runs on electricity". (5) efficiency#1 - (n) the ratio of the output to the input of any system.

No.	Name	Semantic Relatedness Metrics							
		WUP	JCN	LCH	LIN	RES	PATH	LESK	HSO
1	water#1	0.444	0.102	1.291	0.391	3.138	0.091	59	0
2	efficiency#1								
3	water#2	0.267	0.049	1.204	0	0	0.083	34	0
4	efficiency#1								
5	electricity#1	0.267	0.054	1.204	0	0	0.083	26	0
6	efficiency#1								
7	electricity#2	0.25	0.052	1.124	0	0	0.077	31	0
8	efficiency#1								

APPENDIX C: SUPPLEMENTARY MATERIALS FOR STUDY 2

From the billing information provided, indicate how efficient or inefficient the **overall** consumption level for the **household** is, for **both utility types** (for the last 6 months).

Figure C1. A sample experimental rating question for ‘overall’ utility efficiency employed in the experiment.

Table C1. The descriptive statistics for participants' efficiency judgement ratings on all three dimensions

	Mean	SD	SE
Overall	54.16	16.47	0.14
Electricity	53.41	19.98	0.17
Water	54.32	20.29	0.17

APPENDIX D: SUPPLEMENTARY MATERIALS FOR STUDY 3

Table D1. Summary statistics on participant characteristics across each lighting condition.

	Illumination condition		t-test
	2700K	5600K	
<i>N</i> total	115	117	
<i>Mean</i> Age	21.74	21.59	0.59
<i>SD</i> Age	2.14	2.01	
Males	51	59	0.36
Females	64	58	
<i>Mean</i> Clothing level	0.54	0.55	0.09
<i>SD</i> Clothing level	0.03	0.04	
<i>Mean</i> metabolic rate	1.21	1.22	0.68
<i>SD</i> Metabolic rate	0.15	0.18	
<i>Mean</i> BMI	21.62	21.7	0.87
<i>SD</i> BMI	3.77	4.16	

How do you find the current lighting conditions?

Extremely dim	Dim	Slightly Dim	Comfortable	Slightly bright	Bright	Extremely bright
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How are you feeling in this moment?

Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
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How do you find the air quality in this room?

Perfectly bearable	Slightly difficult to bear	Fairly difficult to bear	Very difficult to bear	Unbearable
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How would you prefer to feel?

Much cooler	Cooler	Slightly cooler	Without change	Slightly warmer	Warmer	Much warmer
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Do you find the current thermal conditions...?

Comfortable	Slightly uncomfortable	Uncomfortable	Very Uncomfortable	Extremely Uncomfortable
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Taking into account your personal preference only, would you rather accept than reject this climatic environment?

Yes
No

Is this environment, in your opinion...?

Perfectly bearable	Slightly difficult to bear	Fairly difficult to bear	Very difficult to bear	Unbearable
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Figure D1. Sample questionnaire item presented to each participant at regular intervals of 10 minutes.

Skin temp	1.0	0.5	0.1	0.0	0.1	0.1	0.1	0.2
T.sens	0.5	1.0	0.4	0.0	0.3	0.4	0.1	0.4
T.discomf	0.1	0.4	1.0	0.0	0.6	0.7	0.1	0.6
F.pref	0.0	0.0	0.0	1.0	-0.0	0.0	-0.0	-0.0
P.Accept	0.1	0.3	0.6	-0.0	1.0	0.5	0.1	0.4
P.Toler	0.1	0.4	0.7	0.0	0.5	1.0	0.1	0.7
Light.Q	0.1	0.1	0.1	-0.0	0.1	0.1	1.0	0.1
Air.Q	0.2	0.4	0.6	-0.0	0.4	0.7	0.1	1.0
	Skin temp	T.sens	T.discomf	F.pref	P.Accept	P.Toler	Light.Q	Air.Q

Figure D2. Repeated measures correlation of all outcome measures items. Significant correlation ($p < .05$) was noted for all items, except for ‘Future preference’ (i.e. ‘*F.pref*’).

Table D2. Summary table of descriptive statistics for each of the subjective environment evaluation ratings

	<i>Mean</i>	<i>SD</i>	<i>SE</i>
Skin Temperature	31.98	1.31	0.03
Thermal Sensation	3.97	1.17	0.03
Thermal Discomfort	1.41	0.81	0.02
Personal Acceptance	0.19	0.39	0.01
Personal Tolerance	1.36	0.71	0.02
Lighting Brightness	4.55	1.05	0.02
Air Quality	1.32	0.64	0.01