reviewed paper

# Measuring the impact of walking environments on brain activation: results from an fNIRS pilot study

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## 1. ABSTRACT

Studying the impact of built urban environments on pedestrians' walking experience can improve our understanding of the environmental factors that influence perceived walkability. This can contribute to the design of pleasant urban environments that promote better health and well-being for city residents. However, evidence-based research on perceptions of walkability is still limited. Research has demonstrated that functional near-infrared spectroscopy (fNIRS), an optical brain imaging technique, can measure cortical neural activation. Some studies have employed fNIRS to investigate brain activation by contrasting built and natural environments; however, little research has used fNIRS to investigate the effect of built urban environments on brain activity. Therefore, the aim of this study was to apply fNIRS to measure the effect of different built urban environments on prefrontal cortex activation. The present article presents preliminary results from a pilot study involving five participants (one female, age 31.4 ± 5.1 years). While we measured their prefrontal cortex (PFC) oxyhemoglobin (HbO) and deoxyhemoglobin (HbR), participants watched nine 20-second videos of urban environments from a pedestrian's perspective in a laboratory setting. Viewing pleasant walking environments led to a significant decrease in HbO concentrations in the right and central regions of the PFC, indicating physiological relaxation. This study demonstrates the feasibility of using fNIRS to study the built environment and opens up promising opportunities to explore the relationship between urban environments and pedestrians' experiences.

## 2. INTRODUCTION

Walking is considered a sustainable transport mode that benefits society in terms of supporting public health (Hanson & Jones, 2015), social well-being, and environmental sustainability (Silvennoinen et al., 2022). The beneficial effects of walking on physical and mental health have been extensively researched (Hanson & Jones, 2015), including in relation to public transport-related walking (Besser & Dannenberg, 2005; Saelens et al., 2014). As a moderate exercise, walking can help prevent chronic illnesses (McKinney et al., 2016) and promote mental health (Kelly et al., 2018). Walking in urban environments can be a stressful experience for pedestrians, with prolonged stress being linked to long-term mental health and well-being (Lederbogen et al., 2011). Although walking has a well-established positive impact, many streets, neighbourhoods and cities are not designed for pedestrians and do not provide a walkable environment that allows or encourages people to walk.

### 2.1 Walking and the built urban environment

The walking friendliness of a built environment is referred to as walkability (Frank et al. 2006). Walkability has been increasingly important in research and as a strategic goal in urban design and transportation practice (Forsyth, 2015). Residential density, street connectivity, and land use mix (also known as the 3 or 5 'Ds') are mesoscale environmental variables that have been found to support walking. Research into environmental characteristics on the micro-scale, such as sidewalk quality, street furniture, and the presence of trees and greenery, is relatively recent (De Vos et al., 2022; Otsuka et al., 2021; Silvennoinen et al., 2022; Talen et al., 2022). Of the four commonly identified walkability needs (convenience, safety, comfort, and attractiveness), most research has focused on convenience and safety, whereas comfort and attractiveness have received less attention (Nakamura, 2021; Silvennoinen et al., 2022). Thus, the factors of the built environment that contribute to the walking experience are not yet well understood or quantified (De Vos et al., 2022; Silvennoinen et al., 2022).

Few studies have investigated the determinants and effects of the built urban environment on walkability, i.e. how pedestrians perceive and experience an environment (De Vos et al., 2022; Silvennoinen et al., 2022). For example, the character of the facades along the pavement is relevant to walking (Ameli et al., 2015; Ewing et al., 2016; Oreskovic et al., 2014; Park et al., 2016; Silvennoinen et al., 2022), the presence of windows on ground level (Ameli et al., 2015; Oreskovic et al., 2014), together with the design of the streetscape and street furniture (Ewing et al., 2016; Shi et al., 2020) and the available shops, services, and amenities (Ewing et al., 2016). Further, the dimensions of street blocks (Singh, 2016), the uniformity of the building pane, the presence of street focal points (Oreskovic et al., 2014), traffic volumes, speed limits, and the density of street and driveway intersections (Petritsch et al., 2006; Schneider, 2015) affect walking. Root et al., (2017) find the overall aesthetics of the environment (i.e. perceived presence of trees, interesting things to look at, attractive sights and buildings) to be associated with walkability. Urban greenery shows a largely positive effect on walking (Ameli et al., 2015; Sarkar et al., 2015; Tsai et al., 2019); however, the impact of greenery on the amount of walking in a particular street remains uncertain (Shuvo et al., 2021).

Nevertheless, there is still a lack of clarity about how walking environments are perceived and which features influence the walking experience. Walkability frameworks often fail to incorporate perceptions of comfort and attractiveness, resulting in a deprioritisation of the micro-level of walkability (Nakamura, 2021; Silvennoinen et al., 2022). Personal reactions, experiences, and interpretations play a crucial role in perceiving environments, making it challenging to assess them objectively (Dörrzapf et al., 2019). A growing number of researchers have proposed frameworks to combine quantitative objective data on the built environment with subjective preferences and perceptions (Dörrzapf et al., 2019; Talen et al., 2022). One approach involves using wearable sensors and other technologies to capture human perceptions and emotions, often through bio-physiological parameters such as skin temperature, heart rate variability (Dörrzapf et al., 2019) or brain activity (Chen et al., 2018; Neale et al., 2019). To this end, the aim of this study is to test a novel methodology for measuring brain activation to investigate the relationship between the built environment and walking experiences. In doing so, we demonstrate the feasibility and potential applications of functional near-infrared spectroscopy (fNIRS) for researching built environments.

## 2.2 Functional near-infrared spectroscopy (fNIRS) in urban research

Alongside other brain monitoring technologies, such as electroencephalography (EEG) and functional magnetic resonance imaging (fMRI), functional near-infrared spectroscopy (fNIRS) is used to measure brain activation. So far, EEG is the most commonly used method in urban research (Ancora et al., 2022). Functional near-infrared spectroscopy (fNIRS) is a non-invasive technique that uses near-infrared light to measure variations in the oxygen levels in the brain. Light absorption properties enable the assessment of changes in the concentration of oxyhaemoglobin (HbO) and deoxyhaemoglobin (HbR) in the superficial layers of the brain, revealing changes in neural activation through neurovascular coupling (Ferrari & Quaresima, 2012). The oxygen concentration provides information about the active areas of the brain during various cognitive tasks or experiences. fNIRS is a promising methodology for research in urban planning, especially for studying the effects of built environments. It is advantageous because it is safe, non-invasive, portable, and allows for research to be carried out in natural settings. Research in neuroscience and human brain imaging has confirmed fNIRS as a valid method for studying sensory processes, emotional responses, cognitive load and perception (Ferrari & Quaresima, 2012; Hoshi et al., 2011; Yanagisawa & Tsunashima, 2015; Yu et al., 2017).

In a recent study, Ancora et al., (2022) comprehensively reviewed all available research investigating the effect of urban and/or natural environments on brain activity using brain imaging technologies (fMRI, fNIRS, EEG, MEG, PET). A structured literature search identified ten fNIRS studies (see Ancora et al., (2022) for details), of which eight were conducted indoors and two outdoors. The research overview shows that all fNIRS studies so far have focused on the measurement of differences in the relaxation effects of nature (cf. Biophilia, Attention-Restoration Theory) (Horiuchi et al., 2014; Zhang et al., 2020) or the effects of nature in comparison to the more stressful urban environment (Joung et al., 2015; J. Lee, 2017; Ochiai et al., 2020; Song et al., 2018, 2020; Yamashita et al., 2021; Yu et al., 2017). The study design, therefore, often focuses on using stressful and unpleasant urban environments as experiment stimuli. For example, Yamashita et al., (2021) investigated mood enhancement while participants viewed images of built and urban environments. The images showed a scene with monotonous and unattractive buildings compared to the natural stimuli. Similarly, Song et al., (2018) investigated the differences in physiological effects of forest and urban environments, with the urban scene represented by rather stimulating and stressful urban pictures. Yu et al., (2017) measured the PFC activation while watching urban and natural video scenes, with the urban stimuli recorded in typical Singapore environments. Joung et al., (2015) and Song et al., (2020) conducted in-situ studies, in which the participants were standing and observing urban and forest environments. Two studies focused on the sound-induced effects of forest and urban sounds on the PFC and autonomic nervous system activity. The natural sounds were a recording of a stream, and the urban sounds were traffic noise (Jo et al., 2019; Ochiai et al., 2020). However, the review paper outlines opportunities for future research, for example, in studying environmental complexity, aesthetics, and perception (Ancora et al., 2022).

To ensure awareness of more recent research on fNIRS since the review conducted by Ancora et al. (2022), we have carried out a structured literature search based on the search procedure and terms developed by Ancora et al. (2022). In this context, we repeated their literature search focusing only on fNIRS studies (see the paper for procedure and keywords). The search was performed in May 2023, dating back to May 2022, in PubMed, Scopus, WoS, and ProQuest. As a result, only one relevant article was identified, which examined the effects of walking in urban environments on women’s health (Shaoming et al., 2023). The study found the transition between different urban environments to result in alterations of activity in the PFC. Further, spatial openness and mixed traffic flow factors were relevant to participants’ perceptions of urban spaces (Shaoming et al., 2023).

## 3. METHOD

We designed a pilot experiment to investigate the effect of different walking environments on participants' brain activation in the prefrontal cortex using fNIRS. This pilot study aimed at testing the stimuli and selecting fewer stimuli for the full experiment. Data on the participants' subjective perceptions of urban environments and their perceived time was collected. This paper focuses only on the pilot fNIRS data.

### 3.1 Experiment procedure

Upon arrival at the experimental room, participants were informed of the experimental procedure and asked to sign the consent form and complete a brief survey. Participants were then seated at a desk facing a screen and mouse, and the fNIRS cap was placed on their heads as per manufacturers' best practice. After the signal check, participants were instructed to sit still during the experiment and follow the instructions on the screen. PsychopPy software (Peirce et al., 2019) was used to present the stimuli and synchronize with the fNIRS and subjectively reported data. The experimental procedure of the entire pilot experiment is displayed in Figure 1. Notably, this study focuses only on the first part of the experiment (video watching). Following the initial instructions, participants watched nine 20-second videos in a randomized order. In between each video, there was a 12-second break. During the 12-second resting state, the participant views a grey screen with a centred white cross. The following procedures, which include time perception tasks and subjective evaluation of videos using Likert scales, were tested for the full experiment. The experiment was concluded with a subjective rating, after which the participants were disconnected from the sensors and debriefed. The experiment had a duration of around 30 minutes.

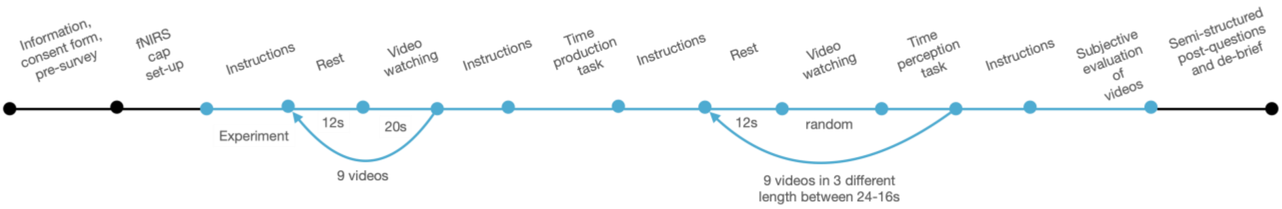



Figure 1: Experimental procedure of the pilot experiment

### 3.2 Stimuli

Nine videos of 20 seconds each were used as experimental stimuli. The recordings were captured in 4k resolution using a gimbaled 3-axis stabilised camera (DJI Pocket 2) in the city of Copenhagen in November 2022. All videos underwent editing and stabilisation using Adobe Premiere Pro 2023. The video recordings were taken from a pedestrian's viewpoint and at a typical walking speed (4-5 km/h). For consistency between the videos, they were recorded under similar weather conditions (cloudy to sunny) and without direct encounters with pedestrians. Screenshots of the videos are presented in Figure 2. Considering this is an exploratory pilot study, a systematic overview of the video characteristics will not be provided. However, there are some differences to be noted. The character of the urban environments shown in the videos differs (to varying degrees) in terms of:

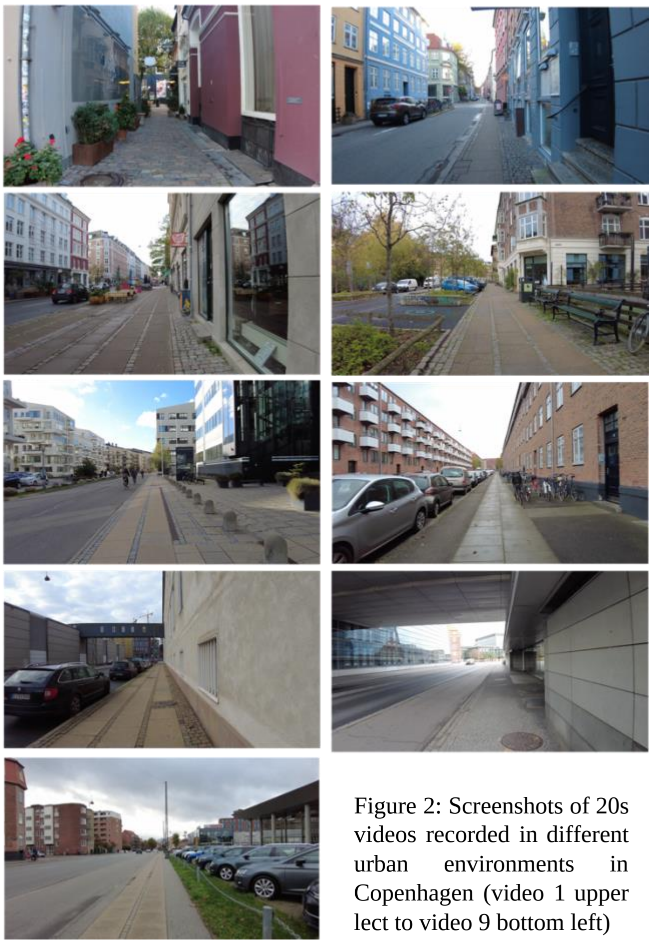


Figure 2: Screenshots of 20s videos recorded in different urban environments in Copenhagen (video 1 upper lect to video 9 bottom left)

- Location (inner city, residential neighbourhood, industrial area)
- Functions (Mixed-use, single-use functions, ground-level use)
- Infrastructure (type of street, speed limit, traffic restrictions, parking, sidewalk, bicycle infrastructure)
- Moving and parked traffic (car and bicycle traffic, pedestrians)
- Urban design and spatial elements (seating, art, spatial elements, light elements, signs)
- Buildings (modern/historical, number, levels, view/lines of vision)
- Facades (openness/transparency, colours, materials, structures, windows, doors)
- Greening (planters, trees, façade greening, plant beds)

### 3.3 Participants

Five healthy participants (mean age 31.4 years; SD=5.1; 1 female) were recruited for the pilot study from the Faculty of Architecture and Design. Exclusion criteria included high caffeine consumption at the time of the experiment, awareness of atypical neurological conditions (such as autism or ADHD), or usage of medication affecting the nervous system. One participant was left-handed, and the others were right-handed. All participants gave their consent to take part in the study. The study was ethically approved according to local regulations.

### 3.4 fNIRS data collection and analysis

#### 3.4.1 Data collection

Brain activity was measured with a continuous-wave system, the NIRSport 2 (NIRx Medical Technologies, Berlin, Germany), that had an 8x8 configuration and short channels. Data from two wavelengths (760 and 850 nm) was sampled at 10.17 Hz. Optodes were arranged in a montage placed on the PFC following the international 10-20 system for EEG electrode placement (Oostenveld & Praamstra, 2001); see Figure 3. The PFC, located in the frontal lobe of the human brain, is associated with higher

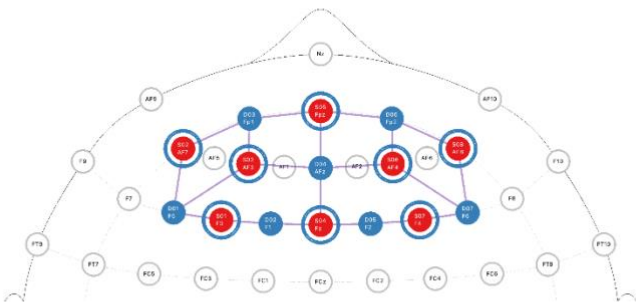


Figure 3: fNIRS montage with 8x8 configuration and short channels (NIRx Medical Technologies)

cognitive processes such as problem-solving and decision-making (Song et al., 2020). Further, the orbitofrontal cortex, located in the PFC, has been identified to play an important role in emotional processes (Rolls & Grabenhorst, 2008). At this early stage of research, it remains unclear which constructs are suitable for studying urban environments. Further research is required to explore and identify the relevant brain regions and constructs for this purpose.

### 3.4.2 Data analysis

The fNIRS data were analysed with the NIRS Brain AnalyzIR Toolbox (Santosa et al., 2018) in MATLAB Version: 9.11.0.1873467 (R2021b) Update 3 (The MathWorks Inc., Natick, Massachusetts). Raw light intensities were converted to optical densities. Thereafter, we applied the TDDR algorithm to correct for motion artifacts (Fishburn et al., 2019), before signal quality check. The signal quality was evaluated by computing the Scalp Coupling Index (SCI) (Pollonini et al., 2016) with QT-NIRS (Montero-Hernandez & Pollonini, 2020/2023). QT-NIRS uses a sliding time window of 5 seconds to calculate SCI over the entire time series, and automatically marks and rejects low-quality channels based on an overall threshold. We used the default threshold (0.75) for the overall quality threshold, which means that at a given SCI threshold, a channel is marked as good if it attains the SCI threshold at least 75% of the time. We evaluated signal quality at two SCI thresholds. For SCI = 0.8, 69.3% of the data were considered high quality. For SCI = 0.6, 75.7% of the data were considered high quality. Since these are pilot data, we selected the lower SCI threshold of 0.6. When considering that this is pilot data, the overall channel quality is quite high.

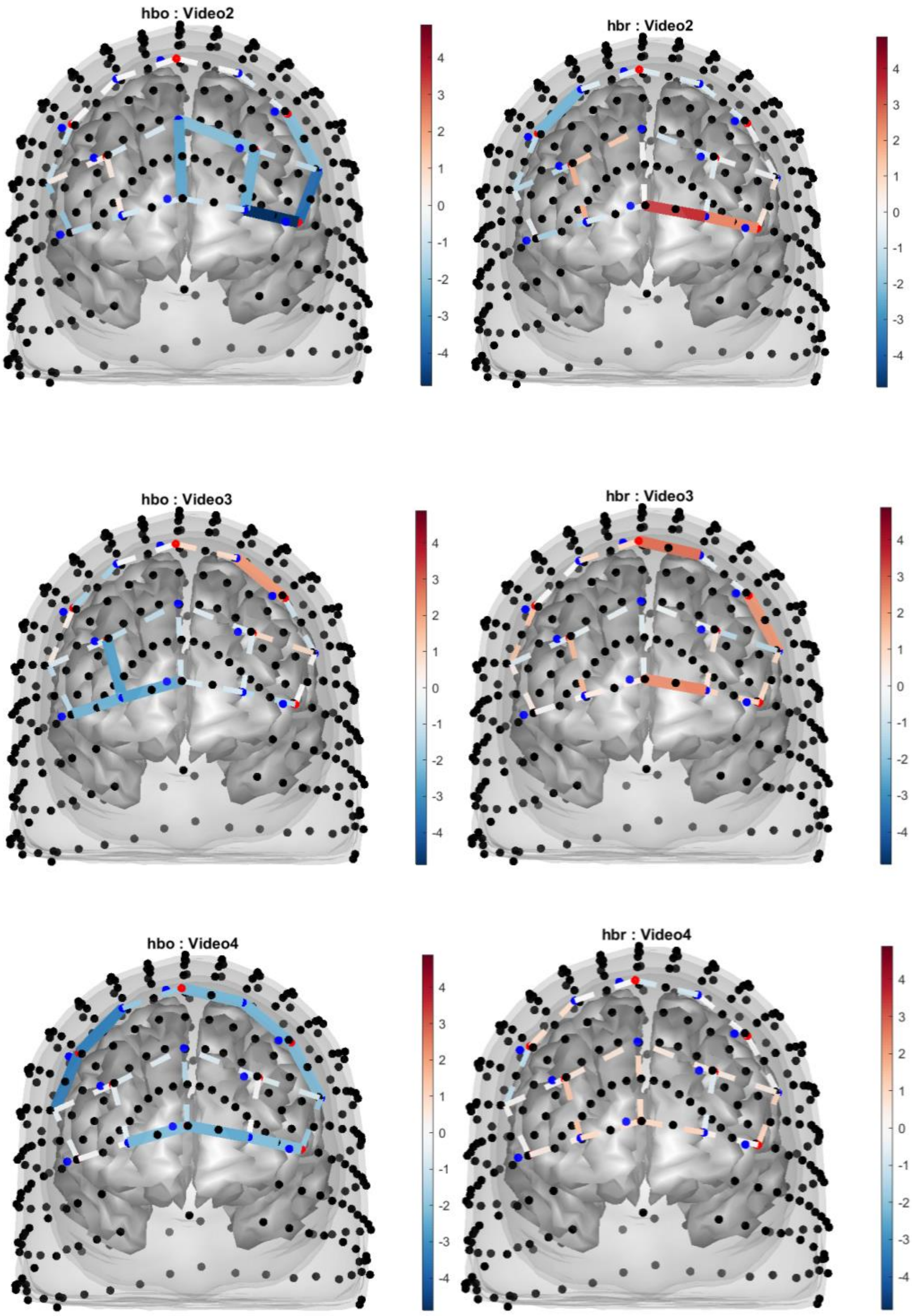
After pruning channels, we converted motion-corrected optical density to hemoglobin concentration changes using the modified Beer-Lambert Law (Delpy et al., 1988) with a 0.1 partial path length factor of 0.1 and extinction coefficient from Jacques (Jaques et al., 2015). For subject-level statistics, the data was first resampled to 4 Hz. Thereafter, we ran a generalised linear model with autoregressive-based prewhitening followed by iteratively reweighted least-squares (Barker et al., 2013, 2016) and short-channel regressors (Santosa et al., 2020), as this performs best in sensitivity-specificity analyses (Santosa et al., 2020). For group-level statistics, we ran a mixed-effects model including the main effect of the condition (i.e., video) and controlling for participants. The results presented are the main effects, i.e., the effects of watching videos on hemodynamic activation compared to baseline (i.e., baseline activation when not watching videos). The Benjamini- Hochberg procedure (Benjamini & Hochberg, 1995) was used to control the false-discovery rate. The corrected p-value is denoted as q.

## 4. RESULTS

The results section presents the main findings from the fNIRS data collection while participants watched the nine videos. To test the videos in this pilot study, we selected the most interesting findings based on visual inspection of the main findings and contrasting the different videos. As this was a pilot study, we compared all the contrasts. Figure 2 shows the results of the main effects of watching the videos compared to the baseline (resting state). We have chosen to highlight some of the results for illustration.

Some significant HbO and HbR level changes were observed as participants watched the videos. When watching video 2, participants showed a significant decrease in blood oxygen (HbO) in one channel, with the other channels also showing a decrease in HbO. The decrease in HbO levels suggests a reduction in cognitive demand among participants while watching video 2. This finding could be interpreted cautiously as a pleasant response and physiological relaxation. We did not find significant results for videos 3 and 4. However, both videos resulted in a decrease in HbO levels in several channels. In particular, video 4 demonstrated a general decrease in HbO levels in almost all channels. In video 6, a slight increase in HbO is observed in ten channels and a larger increase in one channel. Video 8 shows negligible increases in HbO. In comparing the effects of watching different videos, a significant difference in HbO was found in one channel. Figure 3 presents two examples of contrasts. When comparing video 2 to video 8 and video 2 to video 6, a significant decrease in HbO in one channel is observed in the anterior medial superior frontal gyrus (SFG).

Figure 4: Main effects of watching videos 2, 3, 4, 6, 8 HbO (left column) and HbR (right column) levels. The results are illustrated as t-statistic maps plotted onto the colin27 brain atlas, the colour bar represents the t-statistic scaled to [-5, 5], and solid lines indicate statistical significance (q<0.05).



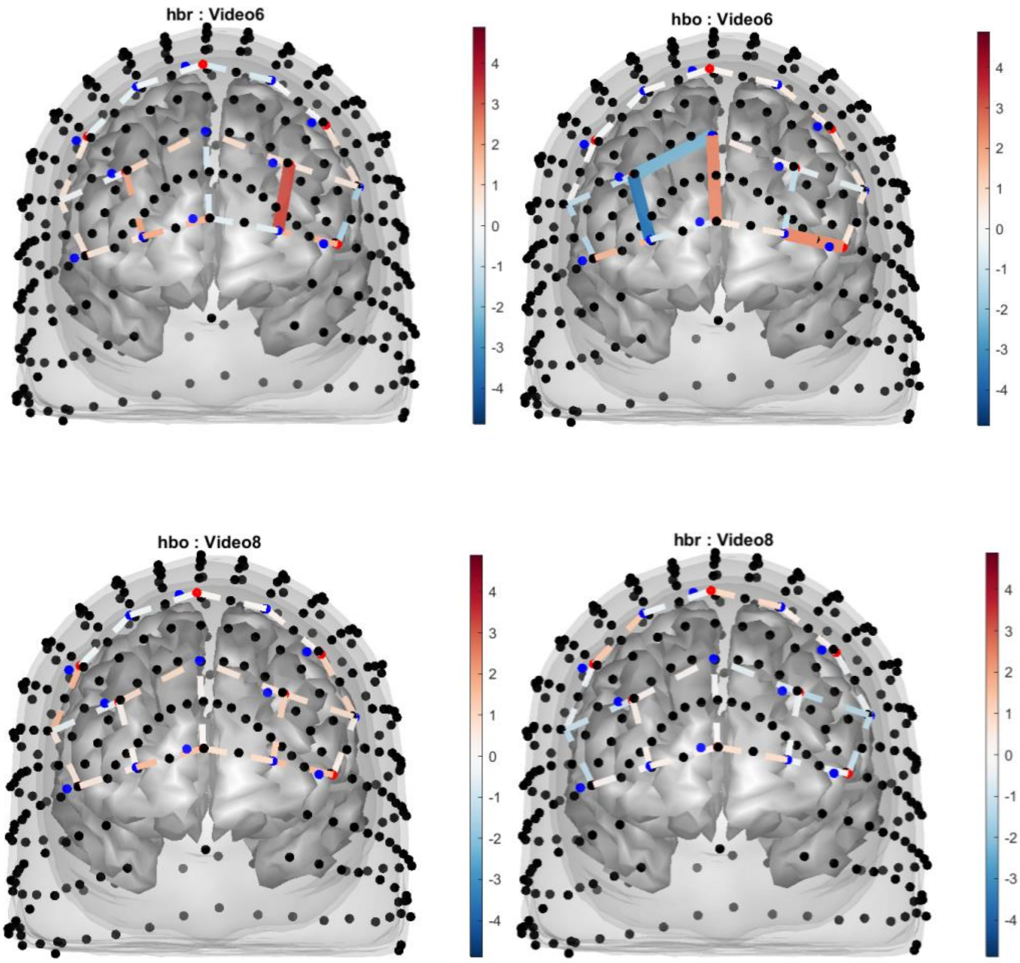
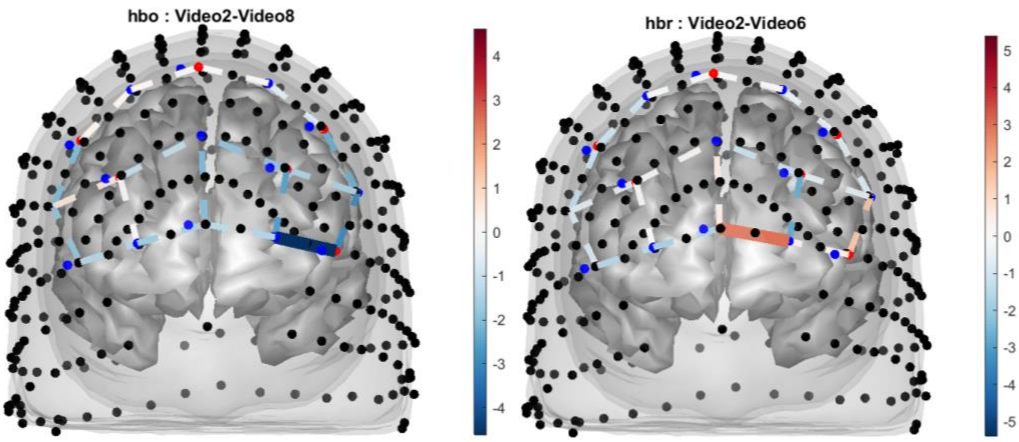
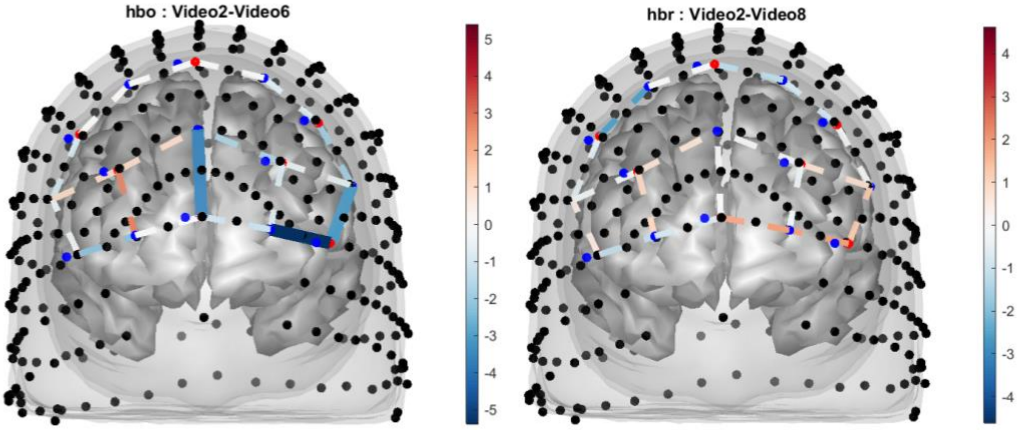



Figure 5: Examples of contrasts, comparing video 2 to videos 6 and 8. Video 2 shows a mixed-use old town street with colourful, diverse, open, and engaging facades and architectural details, small sidewalks but low levels of car traffic due to regulations. Video 6 shows a residential neighbourhood with monotonous architecture in industrial brick style with no variation or integration of other uses, greening or spatial elements. Video 8 shows an inner city street with high levels of traffic and bicycle infrastructure besides the sidewalk, with monotonous and closed facades, no ground-level use on the street side, high noise levels, and little connection to surroundings due to the underpass situation. The contrast showed a significant decrease in HbO when participants watched video 2, in comparison to video 6 and video 8. The results are illustrated as t-statistic maps plotted onto the colin27 brain atlas, the colour bar represents the t-statistic scaled to [-5, 5], and solid lines indicate statistical significance (q<0.05).






## 5. DISCUSSION

The purpose of this pilot study was to test the feasibility of implementing fNIRS for the study of the built environment and to propose fNIRS as a possible interdisciplinary research method for urban planning. Given the small sample size and exploratory nature of this study, we cannot make strong interpretations or conclusions. Despite this limitation, we were able to demonstrate that viewing pleasant walking environments (i.e. video 2, video 3, video 4) was correlated with a decrease in the hemodynamic response in the right and central areas of the PFC. In the context of walkability research, pleasant environments were generally characterised by varied facades, ground-level use, greenery (in video 4), low traffic volumes and the availability of spatial elements (e.g. benches). In contrast, observing less pleasant walking environments (i.e. videos 6 and 8) led to a slight increase in the hemodynamic response. This effect is also noticeable when comparing video 2 with videos 6 and 8. In a direct comparison, video 2 resulted in a significant decrease in HbO levels, i.e. a lower hemodynamic response. Videos 6 and 8 were characterised by monotonous and closed facades, no windows at ground level, no spatial elements or greenery and high traffic volume (video 8). As a result, we can observe differences between more pleasant and relaxing urban environments for walking and more stressful and unpleasant urban environments.

These primary findings are not supported by many other similar studies, but there may be some consistency with previous studies comparing natural and built environments (Song et al., 2020; Yu et al., 2017) or using positive and negative stimuli (Hoshi et al., 2011). Exposure to natural environments (such as forests, parks, etc.) compared to urban environments has been found to decrease the hemodynamic response in the PFC (Song et al., 2020; Yu et al., 2017). Similarly, exposure to unpleasant emotions was associated with an increased hemodynamic response, whereas exposure to pleasant emotions led to a decreased hemodynamic response in the PFC (Hoshi et al., 2011). Studies of nature exposure often use the Attention-Restoration Theory to explain the relaxing effect of natural environments on hemodynamic response. According to this theory, natural environments lead to reduced attentional effort, mental fatigue and cognitive load (Weber & Trojan, 2018; Yu et al., 2017). Although evidence is still limited, the built environment has also been associated with restorative values, e.g. in terms of architectural features such as lower building height, variation in facades, architectural variation, aesthetic values or historic buildings (Weber & Trojan, 2018).

In the context of our study, research on restorative effects may support our findings on the effects of exposure to different types of built environments; that is, participants showed lower hemodynamic responses when they watched videos of a walk past historic buildings with interesting things to look at (video 2) than when they walked past a monotonous facade (video 6) and a busy street (video 8). More specifically, video 2 resulted in a significantly lower hemodynamic response. The video shows a pleasant walk through a historic part of the city centre, with colourful and open facades, shops, restaurants and cafes with outdoor seating, but no greenery. If the participant perceived the video as pleasant, it could have resulted in physiological relaxation and a consequent decrease in the hemodynamic response. Likewise, video 4 caused a reduction in HbO levels. The video shows a mixed residential area with historic buildings and ground-level use and is the video with the most greenery. The video passes several flower beds, trees and benches. There may be a correlation between the decrease in HbO and the relaxing environment, which is likely due to the presence of greenery. Unlike video 2, viewing both video 6 and video 8 resulted in an increased haemodynamic response. Video 6 shows a walk in a monotonous residential area without spatial elements, open facades or greenery. Video 8 shows a walk along a grey, closed facade, under a building and along a busy road with bicycle and car traffic. An increased hemodynamic response may be a consequence of the stressful and dynamic environment shown in the video. These initial interpretations require further examination in the full study.

This pilot study had some limitations. The participants were limited to a few researchers from the Faculty of Architecture with expertise in architecture and urban planning. The full experiment will include a larger sample size of non-architects, representing different age groups and an equal gender distribution. Moreover, the experimental design exclusively focused on the visual representation of the videos. Future experiments could take into account other senses, particularly the auditory sense. Finally, it is worth noting that although the videos showed the urban environment from a pedestrian's perspective, the participants themselves were seated to avoid motion artefacts on the one hand, and physical activity to influence cognitive outcomes on the other (Miyazawa et al., 2013). Future research may consider employing simulated walking setups in the laboratory (e.g. treadmills) or conducting in-situ experiments. Walking is generally associated with increased activation in the PFC (Herold et al., 2017). Additionally, perceptions of the built environment may be linked to physical and rhythmic experiences from an architectural perspective (Papale et al., 2016).

### 5.1 Future research

This pilot study opens up promising opportunities to explore the impact of urban environmental features on the pedestrian experience. A full-scale experiment is being conducted with 50-60 participants and an improved experimental design, including additional data on subjective perceptions of the urban environment, mobility behaviour and socio-demographics. The results will provide insights into the effects of four urban environments (Videos 2, 4, 6 and 8) on brain activation and further implications for walkable urban environments. Implementing fNIRS as a research method in walkability research could be a way to learn more about the factors of the built environment that contribute to the experience of walking environments, such as the effects of certain urban design features, façade design, greening, etc. The level of detail of our findings and discussions is unclear at this stage of the research, as we lack references and constructs to work with. Exploratory research is needed into the relevant brain regions and the constructs to be used.

With the prospect of increasing urbanisation, densification and other future challenges, we need a better understanding of how the urban environment affects health and well-being, and how people experience the environment, particularly in terms of emotions and stress responses. Combining fNIRS with health data and physiological sensors has the potential to advance research on urban health and well-being. Considering social justice, accessibility and feminist planning perspectives, fNIRS appears to be a promising tool for investigating how the environment affects different user groups, including children, older people, people of different genders and identities, people with disabilities, and people from different socio-economic backgrounds. For example, research on diverse groups could explore gender-based differences in perceptions of urban safety, investigate the characteristics of pleasant environments, or gain insight into the perceptions and needs of children and elderly people in the city. To improve the research, scientists should explore the benefits of combining different methods and linking fNIRS data with socio-demographic, health, and qualitative data. The integration of EEG, eye-tracking devices and physiological sensors has great potential for in-situ implementation and the study of urban environments. More pilot studies are required to implement the combination of various methods and technologies, such as virtual and augmented reality.

## 6. CONCLUSIONS

Understanding the determinants and effects of the built environment on the experience of walking in cities is an important step in creating healthy and liveable urban environments for people. However, more research is needed on the microscale and perceptions of comfort and attractiveness to understand the contributing factors to walkability. Advances and access to new technologies and methods from the human and cognitive sciences can help to understand pedestrians´ perceptions and effects on the environment. The main objective of this pilot study was to evaluate the implementation and feasibility of fNIRS for studying the built environment and to suggest employing fNIRS as an interdisciplinary research method in urban planning research. Although the study's primary nature and limitations should be considered, observing pleasant walking environments resulted in a significant decrease in HbO in the right and central areas of the PFC, compared to observing boring and stressful walking environments. The environments varied in the facades' character, level of greenery, traffic, and spatial components. These preliminary results could suggest that exposure to positively perceived walking environments results in lower HbO concentrations, which may be interpreted as physiological relaxation and an overall pleasant and less stressful experience for the pedestrian. While further research is needed, this study demonstrates the feasibility of using fNIRS to study the built urban environment and opens up promising opportunities to explore the relationship between people and the urban environment.

## REFERENCES

Ameli, S. H., Hamidi, S., Garfinkel-Castro, A., & Ewing, R. (2015). Do Better Urban Design Qualities Lead to More Walking in Salt Lake City, Utah? *Journal of Urban Design*, *20*(3), 393–410. https://doi.org/10.1080/13574809.2015.1041894

Ancora, L. A., Blanco-Mora, D. A., Alves, I., Bonifácio, A., Morgado, P., & Miranda, B. (2022). Cities and neuroscience research: A systematic literature review. *Frontiers in Psychiatry*, *13*, 983352. https://doi.org/10.3389/fpsyt.2022.983352

Barker, J. W., Aarabi, A., & Huppert, T. J. (2013). Autoregressive model based algorithm for correcting motion and serially correlated errors in fNIRS. *Biomedical Optics Express*, *4*(8), 1366–1379. https://doi.org/10.1364/BOE.4.001366

Barker, J. W., Rosso, A. L., Sparto, P. J., & Huppert, T. J. (2016). Correction of motion artifacts and serial correlations for real-time functional near-infrared spectroscopy. *Neurophotonics*, *3*(3), 031410. https://doi.org/10.1117/1.NPh.3.3.031410

Benjamini, Y., & Hochberg, Y. (1995). Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing. *Journal of the Royal Statistical Society: Series B (Methodological)*, *57*(1), 289–300. https://doi.org/10.1111/j.2517-6161.1995.tb02031.x

Besser, L. M., & Dannenberg, A. L. (2005). Walking to public transit: Steps to help meet physical activity recommendations. *American Journal of Preventive Medicine*, *29*(4), 273–280. https://doi.org/10.1016/j.amepre.2005.06.010

Chen, Z., Schulz, S., Qiu, M., Yang, W., He, X., Wang, Z., & Yang, L. (2018). Assessing affective experience of in-situ environmental walk via wearable biosensors for evidence-based design. *Cognitive Systems Research*, *52*, 970–977. https://doi.org/10.1016/j.cogsys.2018.09.003

De Vos, J., Lättman, K., van der Vlugt, A.-L., Welsch, J., & Otsuka, N. (2022). Determinants and effects of perceived walkability: A literature review, conceptual model and research agenda. *Transport Reviews*, 1–22. https://doi.org/10.1080/01441647.2022.2101072

Delpy, D. T., Cope, M., Zee, P. van der, Arridge, S., Wray, S., & Wyatt, J. (1988). Estimation of optical pathlength through tissue from direct time of flight measurement. *Physics in Medicine & Biology*, *33*(12), 1433. https://doi.org/10.1088/0031-9155/33/12/008

Dörrzapf, L., Kovács-Győri, A., Resch, B., & Zeile, P. (2019). Defining and assessing walkability: A concept for an integrated approach using surveys, biosensors and geospatial analysis. *Urban Development Issues*, *62*(1), 5–15. https://doi.org/10.2478/udi-2019-0008

Ewing, R., Hajrasouliha, A., Neckerman, K. M., Purciel-Hill, M., & Greene, W. (2016). Streetscape Features Related to Pedestrian Activity. *Journal of Planning Education and Research*, *36*(1), 5–15. https://doi.org/10.1177/0739456X15591585

Ferrari, M., & Quaresima, V. (2012). A brief review on the history of human functional near-infrared spectroscopy (fNIRS) development and fields of application. *NeuroImage*, *63*(2), 921–935. https://doi.org/10.1016/j.neuroimage.2012.03.049

Fishburn, F. A., Ludlum, R. S., Vaidya, C. J., & Medvedev, A. V. (2019). Temporal Derivative Distribution Repair (TDDR): A motion correction method for fNIRS. *NeuroImage*, *184*, 171–179. https://doi.org/10.1016/j.neuroimage.2018.09.025

Forsyth, A. (2015). What is a walkable place? The walkability debate in urban design. *Urban Design International*, *20*(4), 274–292. https://doi.org/10.1057/udi.2015.22

Frank, L. D., Sallis, J. F., Conway, T. L., Chapman, J. E., Saelens, B. E., & Bachman, W. (2006). Many Pathways from Land Use to Health: Associations between Neighborhood Walkability and Active Transportation, Body Mass Index, and Air Quality. *Journal of the American Planning Association*, *72*(1), 75–87. https://doi.org/10.1080/01944360608976725

Hanson, S., & Jones, A. (2015). Is there evidence that walking groups have health benefits? A systematic review and meta-analysis. *British Journal of Sports Medicine*, *49*(11), 710–715. https://doi.org/10.1136/bjsports-2014-094157

Herold, F., Wiegel, P., Scholkmann, F., Thiers, A., Hamacher, D., & Schega, L. (2017). Functional near-infrared spectroscopy in movement science: A systematic review on cortical activity in postural and walking tasks. *Neurophotonics*, *4*(4), 041403. https://doi.org/10.1117/1.NPh.4.4.041403

Horiuchi, M., Endo, J., Takayama, N., Murase, K., Nishiyama, N., Saito, H., & Fujiwara, A. (2014). Impact of Viewing vs. Not Viewing a Real Forest on Physiological and Psychological Responses in the Same Setting. *International Journal of Environmental Research and Public Health*, *11*(10), 10883–10901. https://doi.org/10.3390/ijerph111010883

Hoshi, Y., Huang, J., Kohri, S., Iguchi, Y., Naya, M., Okamoto, T., & Ono, S. (2011). Recognition of Human Emotions from Cerebral Blood Flow Changes in the Frontal Region: A Study with Event-Related Near-Infrared Spectroscopy. *Journal of Neuroimaging*, *21*(2), e94–e101. https://doi.org/10.1111/j.1552-6569.2009.00454.x

Jaques, N., Taylor, S., Azaria, A., Ghandeharioun, A., Sano, A., & Picard, R. (2015). Predicting students' happiness from physiology, phone, mobility, and behavioral data. *2015 International Conference on Affective Computing and Intelligent Interaction (ACII)*, 222–228. https://doi.org/10.1109/ACII.2015.7344575

Jo, H., Song, C., Ikei, H., Enomoto, S., Kobayashi, H., & Miyazaki, Y. (2019). Physiological and Psychological Effects of Forest and Urban Sounds Using High-Resolution Sound Sources. *International Journal of Environmental Research and Public Health*, *16*(15), Article 15. https://doi.org/10.3390/ijerph16152649

Joung, D., Kim, G., Choi, Y., Lim, H., Park, S., Woo, J.-M., & Park, B.-J. (2015). The Prefrontal Cortex Activity and Psychological Effects of Viewing Forest Landscapes in Autumn Season. *International Journal of Environmental Research and Public Health*, *12*(7), 7235–7243. https://doi.org/10.3390/ijerph120707235

Kelly, P., Williamson, C., Niven, A. G., Hunter, R., Mutrie, N., & Richards, J. (2018). Walking on sunshine: Scoping review of the evidence for walking and mental health. *British Journal of Sports Medicine*, *52*(12), 800–806. https://doi.org/10.1136/bjsports-2017-098827

Lederbogen, F., Kirsch, P., Haddad, L., Streit, F., Tost, H., Schuch, P., Wüst, S., Pruessner, J. C., Rietschel, M., Deuschle, M., & Meyer-Lindenberg, A. (2011). City living and urban upbringing affect neural social stress processing in humans. *Nature*, *474*(7352), 498–501. https://doi.org/10.1038/nature10190

Lee, I.-M., Shiroma, E. J., Lobelo, F., Puska, P., Blair, S. N., Katzmarzyk, P. T., & Lancet Physical Activity Series Working Group. (2012). Effect of physical inactivity on major non-communicable diseases worldwide: An analysis of burden of disease and life expectancy. *Lancet (London, England)*, *380*(9838), 219–229. https://doi.org/10.1016/S0140-6736(12)61031-9

Lee, J. (2017). Experimental Study on the Health Benefits of Garden Landscape. *International Journal of Environmental Research and Public Health*, *14*(7), 829. https://doi.org/10.3390/ijerph14070829

McKinney, J., Lithwick, D. J., Morrison, B. N., Nazzari, H., Isserow, S. H., Heilbron, B., & Krahn, A. D. (2016). The health benefits of physical activity and cardiorespiratory fitness. *British Columbia Medical Journal*, *58*(3), 131–137.

Miyazawa, T., Horiuchi, M., Komine, H., Sugawara, J., Fadel, P. J., & Ogoh, S. (2013). Skin blood flow influences cerebral oxygenation measured by near-infrared spectroscopy during dynamic exercise. *European Journal of Applied Physiology*, *113*(11), 2841–2848. https://doi.org/10.1007/s00421-013-2723-7

Montero-Hernandez, S., & Pollonini, L. (2023). *QT-NIRS (Quality Testing of Near Infrared Scans)* [MATLAB]. https://github.com/lpollonini/qt-nirs (Original work published 2020)

Nakamura, K. (2021). Experimental analysis of walkability evaluation using virtual reality application. *Environment and Planning B: Urban Analytics and City Science*, *48*(8), 2481–2496. https://doi.org/10.1177/2399808320980747

Neale, C., Aspinall, P., Roe, J., Tilley, S., Mavros, P., Cinderby, S., Coyne, R., Thin, N., & Ward Thompson, C. (2019). The impact of walking in different urban environments on brain activity in older people. *Cities & Health*, *4*, 1–13. https://doi.org/10.1080/23748834.2019.1619893

Ochiai, H., Song, C., Jo, H., Oishi, M., Imai, M., & Miyazaki, Y. (2020). Relaxing Effect Induced by Forest Sound in Patients with Gambling Disorder. *Sustainability*, *12*(15), Article 15. https://doi.org/10.3390/su12155969

Oostenveld, R., & Praamstra, P. (2001). The five percent electrode system for high-resolution EEG and ERP measurements. *Clinical Neurophysiology*, *112*(4), 713–719. https://doi.org/10.1016/S1388-2457(00)00527-7

Oreskovic, N. M., Charles, P. R. S. L., Shepherd, D. T. K., Nelson, K. P., & Bar, M. (2014). ATTRIBUTES OF FORM IN THE BUILT ENVIRONMENT THAT INFLUENCE PERCEIVED WALKABILITY. *Journal of Architectural and Planning Research*, *31*(3), 218–232.

Otsuka, N., Wittowsky, D., Damerau, M., & Gerten, C. (2021). Walkability assessment for urban areas around railway stations along the Rhine-Alpine Corridor. *Journal of Transport Geography*, *93*, 103081. https://doi.org/10.1016/j.jtrangeo.2021.103081

Papale, P., Chiesi, L., Rampinini, A. C., Pietrini, P., & Ricciardi, E. (2016). When Neuroscience 'Touches' Architecture: From Hapticity to a Supramodal Functioning of the Human Brain. *Frontiers in Psychology*, *7*, 866. https://doi.org/10.3389/fpsyg.2016.00866

Park, S., Choi, K., & Lee, J. S. (2016). Operationalization of Path Walkability for Sustainable Transportation. *International Journal of Sustainable Transportation*, *11*, 00–00. https://doi.org/10.1080/15568318.2016.1226996

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., & Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods*, *51*(1), 195–203. https://doi.org/10.3758/s13428-018-01193-y

Petritsch, T. A., Landis, B. W., McLeod, P. S., Huang, H. F., Challa, S., Skaggs, C. L., Guttenplan, M., & Vattikuti, V. (2006). Pedestrian Level-of-Service Model for Urban Arterial Facilities with Sidewalks. *Transportation Research Record*, *1982*(1), 84–89. https://doi.org/10.1177/0361198106198200111

Pollonini, L., Bortfeld, H., & Oghalai, J. S. (2016). PHOEBE: a method for real time mapping of optodes-scalp coupling in functional near-infrared spectroscopy. *Biomed. Opt. Express*, *7*(12), 5104–5119. https://doi.org/10.1364/BOE.7.005104

Rolls, E. T., & Grabenhorst, F. (2008). The orbitofrontal cortex and beyond: From affect to decision-making. *Progress in Neurobiology*, *86*(3), 216–244. https://doi.org/10.1016/j.pneurobio.2008.09.001

Root, E. D., Silbernagel, K., & Litt, J. S. (2017). Unpacking healthy landscapes: Empirical assessment of neighborhood aesthetic ratings in an urban setting. *Landscape and Urban Planning*, *168*, 38–47. https://doi.org/10.1016/j.landurbplan.2017.09.028

Saelens, B. E., Moudon, A. V., Kang, B., Hurvitz, P. M., & Zhou, C. (2014). Relation Between Higher Physical Activity and Public Transit Use. *American Journal of Public Health*, *104*(5), 854–854. https://doi.org/10.2105/AJPH.2013.301696

Santosa, H., Zhai, X., Fishburn, F., & Huppert, T. (2018). The NIRS Brain AnalyzIR Toolbox. *Algorithms*, *11*(5), Article 5. https://doi.org/10.3390/a11050073

Santosa, H., Zhai, X., Fishburn, F., Sparto, P. J., & Huppert, T. J. (2020). Quantitative comparison of correction techniques for removing systemic physiological signal in functional near-infrared spectroscopy studies. *Neurophotonics*, *7*(3), 035009. https://doi.org/10.1117/1.NPh.7.3.035009

Sarkar, C., Webster, C., Pryor, M., Tang, D., Melbourne, S., XiaoHu, Z., & JianZheng, L. (2015). Exploring associations between urban green, street design and walking: Results from the Greater London boroughs. *Landscape and Urban Planning*, *143*, 112–125.

Schneider, R. (2015). Walk or Drive between Stores? Designing Neighbourhood Shopping Districts for Pedestrian Activity. *Journal of Urban Design*, *20*. https://doi.org/10.1080/13574809.2015.1009014

Shaoming, Z., Yuan, Y., & Linting, W. (2023). Impacts of Urban Environment on Women's Emotional Health and Planning Improving Strategies: An Empirical Study of Guangzhou Based on Neuroscience Experiments. *China City Planning Review*, *32*(1), 17–27.

Shi, X., Bosia, D., & Savio, L. (2020). The Influence Factor for Walkability of Street Furniture: In Case of Turin. In J. Charytonowicz & C. Falcão (Eds.), *Advances in Human Factors in Architecture, Sustainable Urban Planning and Infrastructure* (pp. 347–357). Springer International Publishing. https://doi.org/10.1007/978-3-030-20151-7_33

Shuvo, F. K., Mazumdar, S., & Labib, S. M. (2021). Walkability and Greenness Do Not Walk Together: Investigating Associations between Greenness and Walkability in a Large Metropolitan City Context. *International Journal of Environmental Research and Public Health*, *18*(9), Article 9. https://doi.org/10.3390/ijerph18094429

Silvennoinen, H., Kuliga, S., Herthogs, P., Recchia, D. R., & Tunçer, B. (2022). Effects of Gehl's urban design guidelines on walkability: A virtual reality experiment in Singaporean public housing estates. *Environment and Planning B: Urban Analytics and City Science*, *49*(9), 2409–2428. https://doi.org/10.1177/23998083221091822

Singh, R. (2016). Factors Affecting Walkability of Neighborhoods. *Procedia - Social and Behavioral Sciences*, *216*. https://trid.trb.org/view/1396002

Song, C., Ikei, H., Kagawa, T., & Miyazaki, Y. (2020). Effect of Viewing Real Forest Landscapes on Brain Activity. *Sustainability*, *12*(16), Article 16. https://doi.org/10.3390/su12166601

Song, C., Ikei, H., & Miyazaki, Y. (2018). Physiological Effects of Visual Stimulation with Forest Imagery. *International Journal of Environmental Research and Public Health*, *15*(2), 213. https://doi.org/10.3390/ijerph15020213

Talen, E., Choe, K. W., Akcelik, G. N., Berman, M. G., & Meidenbauer, K. L. (2022). Street design preference: An on-line survey. *Journal of Urban Design*, 1–24. https://doi.org/10.1080/13574809.2022.2066512

Timms, P., & Tight, M. (2010). Aesthetic aspects of walking and cycling. *Built Environment*, *36*(4), 487–503. https://doi.org/10.2148/BENV.36.4.487

Tsai, W.-L., Yngve, L., Zhou, Y., Beyer, K. M. M., Bersch, A., Malecki, K. M., & Jackson, L. E. (2019). Street-level neighborhood greenery linked to active transportation: A case study in Milwaukee and Green Bay, WI, USA. *Landscape and Urban Planning*, *191*, 103619. https://doi.org/10.1016/j.landurbplan.2019.103619

Weber, A. M., & Trojan, J. (2018). The Restorative Value of the Urban Environment: A Systematic Review of the Existing Literature. *Environmental Health Insights*, *12*, 1178630218812805. https://doi.org/10.1177/1178630218812805

Yamashita, R., Chen, C., Matsubara, T., Hagiwara, K., Inamura, M., Aga, K., Hirotsu, M., Seki, T., Takao, A., Nakagawa, E., Kobayashi, A., Fujii, Y., Hirata, K., Ikei, H., Miyazaki, Y., & Nakagawa, S. (2021). The Mood-Improving Effect of Viewing Images of Nature and Its Neural Substrate. *International Journal of Environmental Research and Public Health*, *18*(10), 5500. https://doi.org/10.3390/ijerph18105500

Yanagisawa, K., & Tsunashima, H. (2015). Evaluation of pleasant and unpleasant emotions evoked by visual stimuli using NIRS. *2015 15th International Conference on Control, Automation and Systems (ICCAS)*, 383–388. https://doi.org/10.1109/ICCAS.2015.7364944

Yu, J., Ang, K. K., Ho, S. H., Sia, A., & Ho, R. (2017). Prefrontal cortical activation while viewing urban and garden scenes: A pilot fNIRS study. *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS*, 2546–2549. https://doi.org/10.1109/EMBC.2017.8037376

Zhang, Z., Olszewska-Guizzo, A., Husain, S. F., Bose, J., Choi, J., Tan, W., Wang, J., Xuan Tran, B., Wang, B., Jin, Y., Xuan, W., Yan, P., Li, M., Ho, C. S. H., & Ho, R. (2020). Brief Relaxation Practice Induces Significantly More Prefrontal Cortex Activation during Arithmetic Tasks Comparing to Viewing Greenery Images as Revealed by Functional Near-Infrared Spectroscopy (fNIRS). *International Journal of Environmental Research and Public Health*, *17*(22), 8366. https://doi.org/10.3390/ijerph17228366