INTERNATIONAL DESIGN CONFERENCE – DESIGN 2024
https://doi.org/10.1017/pds.2024.97

Investigating differences in brain activity between physical and digital prototyping in open and constrained design tasks

Henrikke Dybvik [1,2,✉], Adam McClenaghan [2], Mariya Stefanova Stoyanova Bond [1], Asbjørn Svergja [1], Tripp Shealy [3], Chris Snider [2], Pasi Aalto [1], Martin Steinert [1] and Mark Goudswaard [2]

[1] Norwegian University of Science and Technology, Norway, [2] University of Bristol, United Kingdom,
[3] Virginia Tech, United States of America

✉ henrikke.dybvik@bristol.ac.uk

Abstract

This article presents an fNIRS experiment investigating cognitive differences between physical and digital prototyping methods in designers (N=25) engaged in open and constrained design tasks. Initial results suggest that physical prototyping yields increased hemodynamic response (i.e., brain activity) compared to digital design, and that constrained design yields increased hemodynamic response compared to open design, in the prefrontal cortex. Further work will seek to triangulate results by investigating potential correlations to design processes and design outputs.

Keywords: design cognition, prototyping, virtual prototyping, computer-aided design (CAD), design activities

1. Introduction and background

Prototyping is a critical part of the product development process (Houde and Hill, 1997). There exists a vast selection of prototyping methods, on a spectrum from fully physical to fully digital (Goudswaard et al., 2021b; Kent et al., 2021, 2021). Different prototyping methods have different affordances, benefits and limitations, which influences the outcome of the prototyping activity, and typical product development processes therefore use a range of prototyping methods, including prototyping techniques from both the physical and the digital domain (Goudswaard et al., 2021a). However, the choice of prototyping method is not trivial, and it remains to be determined whether there is a best prototyping method for a given activity (Lim et al., 2008). Comparing the physical and digital domains independently of the prototyping technique is challenging because such tools often do not translate between domains. Prior studies suggest that increased creativity and communication are associated with physical prototyping (Donati and Vignoli, 2015; Mathias et al., 2018), as is the speed of idea generation (Häggman et al., 2015). Physical prototyping can encourage collaboration and exploration, whereas digital prototyping better handles detailed design work, but is prone to design fixation. Understanding the effects of both physical and digital prototyping methods on design cognition, design process, and design outcome, is necessary to best utilize each prototyping tool to their ability. This becomes even more important with the recent rise in newer digital prototyping technologies (e.g., Unity), and prototyping technologies uniting the digital and physical domains (e.g., mixed reality) (Kent et al., 2021). Moreover, in today's digital society, there is a reliance on a plethora of digital communication media (e.g., video conferencing platforms), with remote collaboration also occurring in design activities (Balters et al., 2023b, 2023a). However, emerging neuroimaging evidence suggests that digital media are inadequate substitutes for traditional in-person social interactions, as altered patterns of interpersonal neuronal synchrony and reduced prosocial behaviour is associated with digital interactions (Balters et al., 2023b). The cognitive interpersonal difference between physical and digital interaction is important as prototyping is often used as a tool for communication (Jensen, 2017; Kent et al., 2021).

Relatively few studies have investigated the effects of prototyping domain on design cognition, although prototyping methods have been characterised and compared (Goudswaard et al., 2021b, 2021a; Kent et al., 2021). Evidence from an electroencephalography (EEG) experiment suggests there is a difference between physical and digital prototyping methods, and recommended further research be conducted with functional near-infrared spectroscopy (fNIRS) (McClenaghan et al., 2023). Design cognition studies have used neuroimaging tools to investigate differences between more open and more constrained design tasks and concept generation techniques. An EEG study of open and constrained design tasks found significantly different brain activation between constrained design tasks (based on problem-solving) and open design tasks (based on sketching) (Vieira et al., 2020b, 2020a). An fNIRS study of engineering design problems with and without added sustainability constraints found significantly different brain activity (Hu et al., 2021).

While the cognitive effects of prototyping domain and the level of constraints in design tasks have been investigated to some extent, the effects of the prototyping domain (physical and digital) and constraints (open or constrained) on design cognition, the design process, and design output, are under-explored. This article begins to address this knowledge gap by presenting initial results from an fNIRS experiment of physical and digital prototyping for open and constrained design tasks. The research question was *what differences in brain activation occur between physical and digital prototyping, and between open and constrained design?* The remainder of the article is structured as follows. Section 2 explains the methodology, Section 3 presents results which are discussed in Section 4. Section 5 closes the article with conclusions.

2. Methodology

Based on the background material presented, we posit that there is a difference between digital and physical prototyping and between open and constrained design. To test this, we set up an experiment investigating the neurocognitive difference between: i) digital and physical prototyping; and, ii) open and constrained design. The experiment was an extension of the EEG experiment described previously (McClenaghan et al., 2023), it additionally included open and constrained design tasks. As such, in the research study presented in this article we tested the following hypotheses:

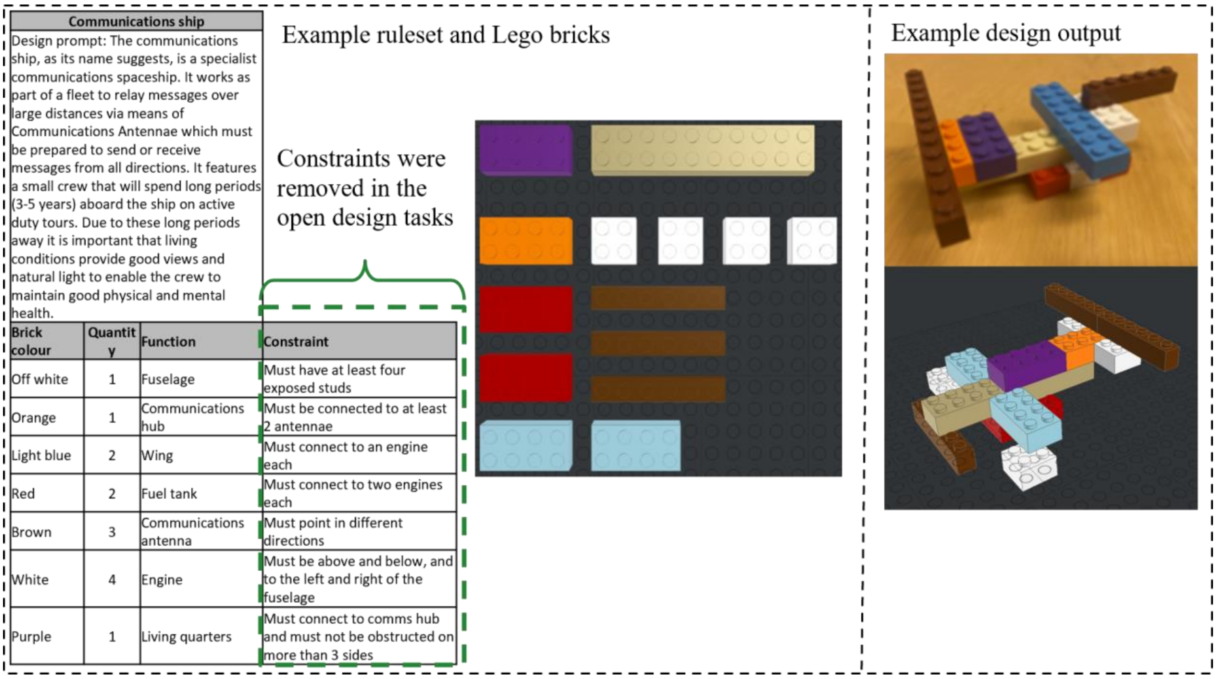
- Hypothesis 1: There is a significant difference in brain activation between physical and digital prototyping; and,
- Hypothesis 2: There is a significant difference in brain activation between constrained and open design.

This section details the experimental task, participants, data capture and data analysis. While numerous dependent variables were measured in the experiment, the scope of this article is to analyse the fNIRS data because it acts as a proxy for, providing insights into, cognitive processes associated with design.

2.1. Experiment design

2.1.1. Task

The task was to design a Lego spaceship using physical or digital Lego. The participants were presented with one design prompt in each task such as that shown in Figure 1 (called ruleset). In the constrained design conditions the spaceship was required to comply with a predetermined set of constraints (see Figure 1). In the open design conditions, the constraints were not shown to participants. The task was self-paced, with a maximum duration of 10 minutes. Each ruleset contained 14 bricks and an equal number of constraints that the design must comply with. Each brick represented a different component and had a constraint associated with it. Five different rule sets were generated (different type of space ship, Lego bricks, and constraints), one for each condition, with different rule sets given to participants for each design task to prevent learning bias, and one ruleset to use in familiarization periods. All rulesets had an equal number of constraints. The rulesets were based on those proposed by Mathias et al. (2018) and extended by McClenaghan et al. (2023). The ruleset order was randomized.



Communications ship			
Design prompt: The communications ship, as its name suggests, is a specialist communications spaceship. It works as part of a fleet to relay messages over large distances via means of Communications Antennae which must be prepared to send or receive messages from all directions. It features a small crew that will spend long periods (3-5 years) aboard the ship on active duty tours. Due to these long periods away it is important that living conditions provide good views and natural light to enable the crew to maintain good physical and mental health.			
Brick colour	**Quantity**	**Function**	**Constraint**
Off white	1	Fuselage	Must have at least four exposed studs
Orange	1	Communications hub	Must be connected to at least 2 antennae
Light blue	2	Wing	Must connect to an engine each
Red	2	Fuel tank	Must connect to two engines each
Brown	3	Communications antenna	Must point in different directions
White	4	Engine	Must be above and below, and to the left and right of the fuselage
Purple	1	Living quarters	Must connect to comms hub and must not be obstructed on more than 3 sides

Figure 1. Example design prompt and ruleset (left) and example design output (right)

2.1.2. Experimental conditions

The experiment consisted of participants completing four design tasks, each with a different design tool and/or level of constrainedness/openness. In other words, two variables, with two levels each, were manipulated in the experiment: openness of design task (levels: open versus constrained design), and prototyping method (levels: physical versus digital design tool). This yielded four conditions:

- Open physical design task;
- Constrained physical design task;
- Open digital design task; and,
- Constrained digital design task.

The condition order followed a 4x4 Latin Square Design for balancing purposes, which yielded 24 permutations (groups). Participants were sequentially assigned to the condition order: i.e., the first participant was assigned to permutation 1, the second participant to permutation 2, etc. We started from the top after reaching 24 participants, i.e., participant 25 was assigned to permutation 1.

2.1.3. Experimental procedure

The experimental procedure is shown in Figure 2. After providing informed consent, participants were fitted with an fNIRS cap before the experiment commenced. Instructions were presented automatically via PsychoPy v2022.2.5 (Peirce et al., 2019). Participants first underwent familiarization periods with the two design tools, which was either physical Lego bricks or digital Lego bricks in LeoCAD, a Lego CAD software (LeoCad, 2022). The experiment ran on a desktop computer (OS: Windows 10 Home 64-bit, CPU: Intel i5-4670K, CPU Speed: 3.98 GHz, GPU: MSI Nvidia GTX 760 4GB, RAM Size: 16GB (4x4GB), RAM Speed: 1867 MHz).

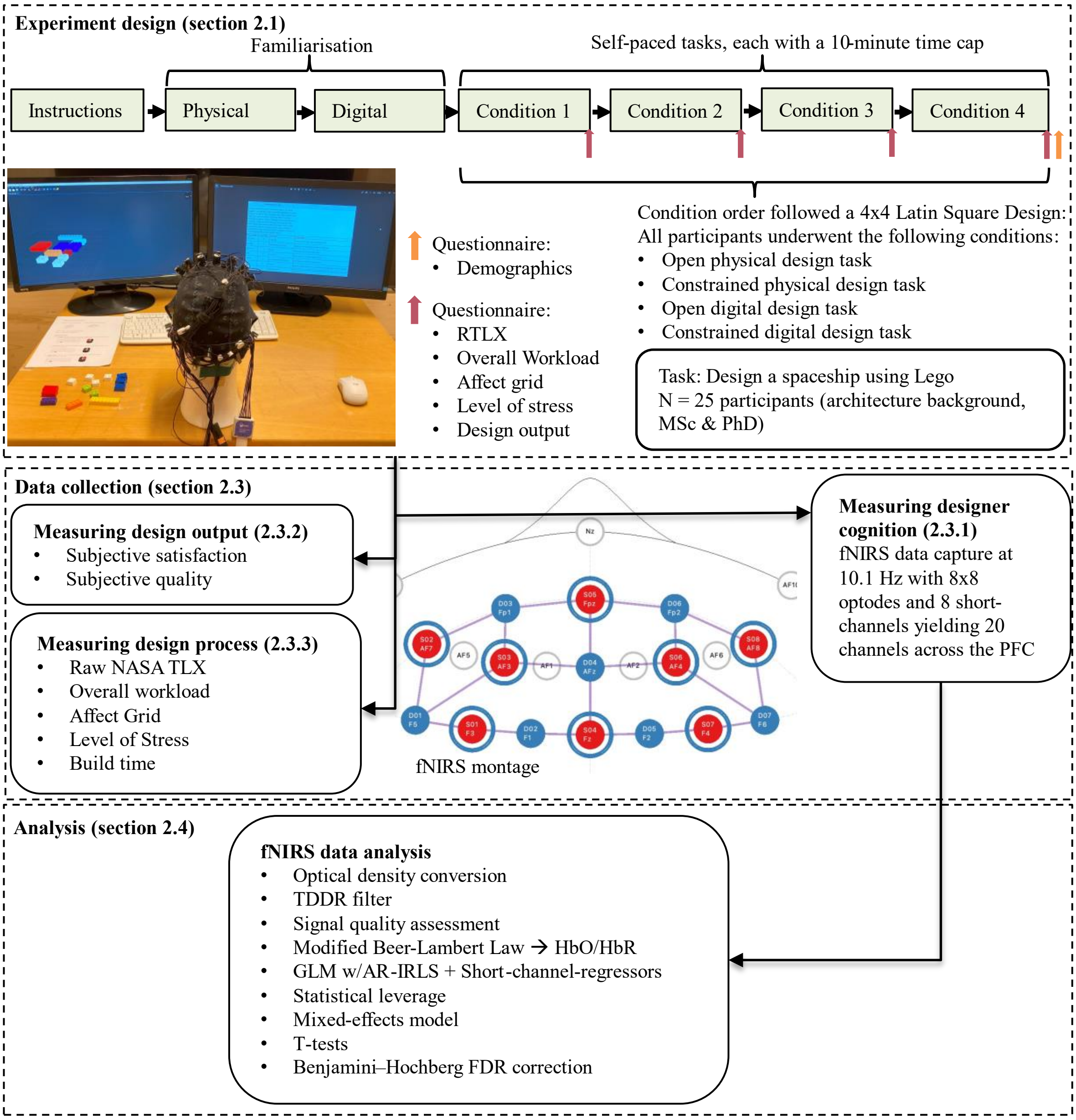


Figure 2. Overview of the methodology used; Reference numbers correspond to section number

2.2. Participants

Healthy participants (N = 27) underwent the experimental procedure after providing written, informed consent. Participants were screened prior to participation: included participants did not have any neurological or psychiatric conditions, take any prescribed medication that could affect brain function (e.g., stimulants, antidepressants, or sleeping medication) or had a history of alcohol or drug abuse. Participants also confirmed that they understood written and spoken English. Ethical approval for the study was obtained from University of Bristol Research Ethics Committee, reference 14498.

Two participants were discarded from the analysis due to technical errors—the experiment was aborted midway for one participant and stimuli triggers were missing for one participant—leaving N = 25 participants for the analysis. There were also two missing triggers, such that for two participants, data for 3 of the 4 conditions were included for analysis. For the N = 25 design participants included in the analysis, 17 were female, and 8 males, and all had a background in architecture (MSc & early PhDs). Four participants were aged 23-25 years, nine were 26-30 years, eight were 31-35 years, three were 36-40 years, and one was above 40 years of age.

2.3. Data collection

2.3.1. fNIRS data collection and montage (measuring designer neurocognition)

fNIRS is an optical neuroimaging technique measuring the hemodynamic response in cortical brain tissue (Ferrari and Quaresima, 2012; Pinti et al., 2020). Increases in neural activation (i.e., brain activity) is related to increases in oxygenated haemoglobin (HbO) and decreases in deoxygenated haemoglobin (HbR) through neurovascular coupling (Leithner and Royl, 2014; Pinti et al., 2020). fNIRS is non-invasive and portable, and is often preferred over EEG and functional magnetic resonance imaging (fMRI) because it is robust to motion artifacts, has higher spatial resolution than EEG and higher temporal resolution than fMRI (Pinti et al., 2020). However, fNIRS is limited to measuring cortical regions (Ferrari and Quaresima, 2012; Pinti et al., 2020).

A continuous-wave NIRSport2 device (NIRx Medical Technologies, LLC, Berlin, Germany) with 8 sources, 8 detectors, and 8 short-channels and NIRx acquisition software Aurora was used to collect fNIRS data at 10.17 Hz. The wavelengths of emitted light (LED sources) were 760 nm and 850 nm. The optodes were arranged in a montage covering the prefrontal cortex (PFC), see Figure 2. The PFC was the region of interest because of its involvement in higher-order cognitive functions such as planning, decision-making, and goal-directed behaviour. Optode placement followed the international 10-10 system for electrode placement (Oostenveld and Praamstra, 2001). The montage covers several subregions (regions of interest (ROIs)) in the PFC: parts of the dorsolateral PFC (dlPFC) (Broadman area 9 and 46), the frontopolar area (FPC) (Broadman area 10), the orbitofrontal area (OFC) (Broadman area 11). These ROIs were determined with fOLD v2.2 (Zimeo Morais et al., 2018).

2.3.2. Design output

We took photos of the physically designed spaceship and saved all LeoCad files, see Figure 1 for an example. After each condition participants performed a subjective assessment of their design output asking them about their level of satisfaction and quality of their design output. Future work will include analysis of design outputs.

2.3.3. Design process

We video recorded participants, and recorded build time. For each condition participants answered a questionnaire inquiring about their design process. We used Raw TLX (RTLX) (Hart, 2006), Overall Workload (Vidulich and Tsang, 1987), Arousal and Valence from the Affect Grid (Russel et al., 1989), and additionally asked about experienced levels of stress. Future work will include analysis of design outputs.

2.4. fNIRS signal processing and statistical analysis

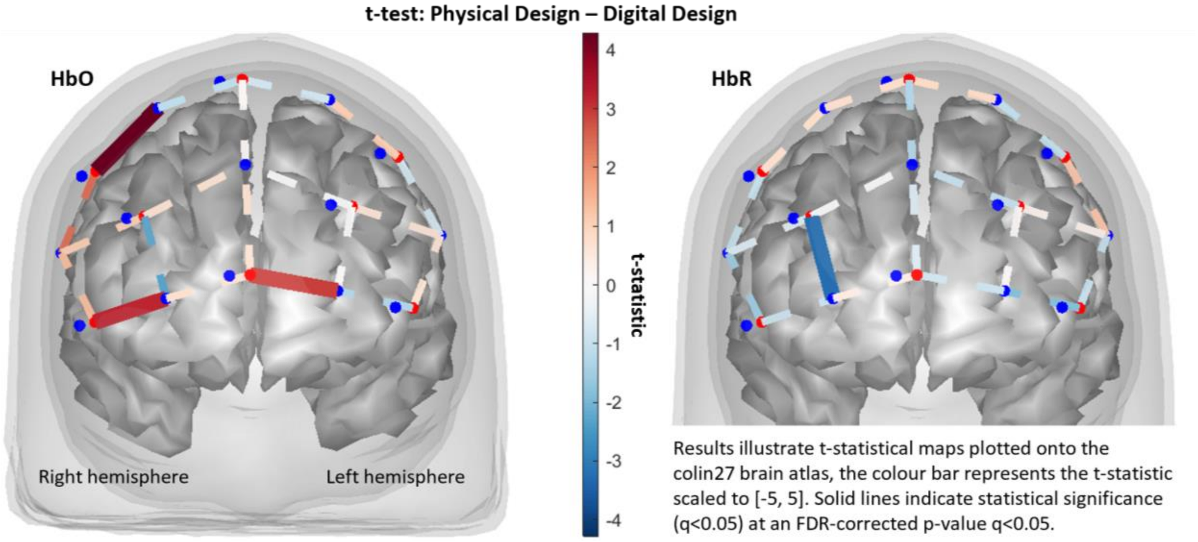
The fNIRS data was analysed with the NIRS Brain AnalyzIR Toolbox (Santosa et al., 2018) in MATLAB R2021b (The MathWorks Inc., Natick, Massachusetts). Raw light intensities were converted to optical density and the timeseries start and end times adjusted to start 15 seconds before the first condition and end 15 seconds after the last condition. Optical density data was Temporal Derivative Distribution Repair (TDDR) corrected (Fishburn et al., 2019) for artefacts before signal quality assessment. Signal quality was assessed by calculating the Scalp Coupling Index (SCI) and Peak Spectral Power (PSP) as implemented by QT-NIRS (Hernandez and Pollonini, 2020; Montero-Hernandez and Pollonini, 2022), which evaluates how often (what percentage of time) the timeseries/data attain an SCI threshold of 0.8 and PSP threshold of 0.1. Channels are automatically labelled as high-quality if SCI ≥ 0.8, 75% or more of the time. In this case 76% of the data were high quality and carried forward in subsequent analysis. Low-quality channels for each participant were discarded. Pruned, motion-corrected optical density data was converted to haemoglobin concentration changes through the modified Beer-Lambert Law (Jacques, 2013) with partial pathlength factor 0.1. Thereafter we ran a general linear model with a canonical hemodynamic response function, the AR-IRLS algorithm (Barker et al., 2016), and short-channels as nuisance regressors for first-level (participant) statistics.

Statistical leverage for a group model was calculated per participant, but no participant was found to have significant leverage, and as such, all participants were retained for group level analysis. For second-level (group) statistics the participant level statistics were fed into a robust mixed-effects model with main effect of condition and participant as a random effect (i.e., controlling for participant). Based on group statistics we computed t-tests between conditions representing the hypotheses. For hypothesis 1 we compared Constrained Physical and Open Physical to Constrained Digital and Open Digital. For hypothesis 2 we compared Constrained Physical and Constrained Digital to Open Physical and Open Digital. The Benjamini–Hochberg procedure was used to control false discovery rate, with the corrected p-value denoted as q (Benjamini and Hochberg, 1995). Results are presented as t-statistical maps plotted onto the colin27 brain atlas using NIRS Brain AnalyzIR Toolbox (Santosa et al., 2018).

3. Results

3.1. Hypothesis 1: Physical versus digital prototyping

There was a significant increase in HbO for three channels covering the frontopolar area/orbitofrontal area (FPC/OFC) (both left and right), and right dorsolateral prefrontal cortex (dlPFC), and a significant decrease in HbR for one channel covering the right OFC, when comparing physical and digital design. See Figure 3 for an illustration of the results and Table 1 for the statistics. This indicates that increased hemodynamic activation (i.e., brain activity) is associated with physical prototyping compared to digital prototyping.



Results illustrate t-statistical maps plotted onto the colin27 brain atlas, the colour bar represents the t-statistic scaled to [-5, 5]. Solid lines indicate statistical significance (q<0.05) at an FDR-corrected p-value q<0.05.

Figure 3. Results for hypothesis 1: Increased hemodynamic activation is associated with physical design compared to digital design

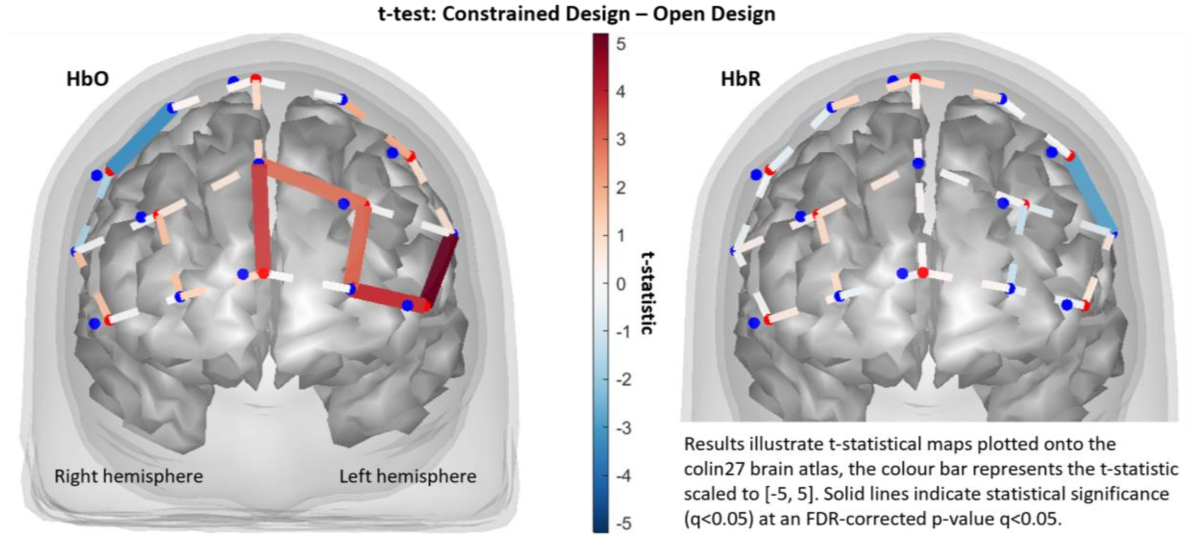
Table 1. Results for hypothesis 1

source	detector	ROI1)	type	beta	se	t-stat	dfe	q	RelativePower
5	3	lFPC/lOFC	HbO	9.12	3.13	2.91	93	0.045	0.25
6	6	rOFC	HbR	-3.08	0.95	-3.50	93	0.024	0.83
7	5	rdlPFC	HbO	13.29	3.10	4.29	93	0.002	0.26
8	6	rFPC/rOFC	HbO	10.66	3.32	3.21	93	0.024	0.24

1) r/l/m prefix indicates right/left/medial respectively

3.2. Hypothesis 2: Constrained versus open design

There was a significant increase in HbO for five channels covering parts of the left dlPFC, medial OFC, and parts of left OFC; a significant decrease in HbO for one channel covering right dlPFC; and a significant decrease in HbR for one channel covering left dlPFC, when comparing constrained and open design. See Figure 4 for an illustration of the results and Table 2 for the statistics. This indicates that increased hemodynamic activation (i.e., brain activity) is associated with constrained design compared to open design for most areas in the PFC showing significant differences, that is, the left dlPFC, medial OFC, and parts of left OFC. However, one channel, covering right dlPFC, exhibited reversed activation, which indicates higher hemodynamic activation (i.e., brain activation) for open design compared to constrained design in that brain region.



Results illustrate t-statistical maps plotted onto the colin27 brain atlas, the colour bar represents the t-statistic scaled to [-5, 5]. Solid lines indicate statistical significance (q<0.05) at an FDR-corrected p-value q<0.05.

Figure 4. Results for hypothesis 2: Increased hemodynamic activation is largely associated with constrained design compared to open design with one exception

Table 2. Results for hypothesis 2

source	detector	ROI[1]	type	beta	se	t-stat	dfe	q	RelativePower
1	1	ldlPFC	HbR	-3.25	1.14	-2.85	93	0.031	0.69
2	1	ldlPFC	HbO	11.61	2.23	5.20	93	4.62e-05	0.35
2	3	lOFC	HbO	11.51	3.09	3.73	93	0.005	0.26
3	3	lOFC	HbO	6.74	2.17	3.11	93	0.020	0.37
3	4	ldlPFC/lOFC	HbO	7.41	2.58	2.87	93	0.031	0.31
5	4	mOFC	HbO	7.97	2.17	3.67	93	0.005	0.36
7	5	rdlPFC	HbO	-9.96	3.09	-3.23	93	0.017	0.26

[1] r/l/m prefix indicates right/left/medial respectively

4. Discussion

The study presented in this article asked *what difference in brain activation occur between physical and digital prototyping, and between open and constrained design?*

4.1. Measurable differences in brain activity

For hypothesis one, comparing physical and digital prototyping we found significantly increased HbO in three channels, and a significant decrease in HbR for one channel. This suggests increased brain activity occurs in physical prototyping than in digital prototyping, in parts of the PFC (FPC/OFC and right dlPFC). These results support hypothesis one, i.e., there seems to be significantly different brain activation between physical and digital prototyping methods. For hypothesis two, comparing constrained and open design we found significantly increased HbO in five channels, and a significant decrease in HbR for one channel. This suggest that increased brain activity occurs in constrained design than in open design,in parts of the PFC (left dlPFC, medial OFC, and parts of left OFC). We further found a significant decrease in HbO in one channel in the right dlPFC, which indicates that higher brain activity occurs in open design than in constrained design. These results support hypothesis two, i.e., there seems to be significantly different brain activation between constrained and open design. The left dlPFC, medial OFC, and parts of left OFC exhibits increased brain activity in constrained design (compared to open), while the right dlPFC exhibits increase brain activity in open design (compared to constrained).

4.2. Comparison of our results to other research

The original EEG study of physical and digital prototyping found overall statistical differences in brain activity, but the findings could not be related to brain ROIs (McClenaghan et al., 2023). Overall, their results were inconclusive, but warranted further investigations. The fNIRS study of sustainability constraints yielded similar results to our; constraining the design process led to increased brain activation in the left dlPFC (Hu et al., 2021). The EEG study of open and constrained design tasks found significantly higher brain activation associated with open design tasks compared to constrained design tasks (Vieira et al., 2020b, 2020a). However, these results are contrary to ours. Compared to Vieira et al., who had three constraints (or conditions) in the constrained problem-solving task, our task had 14 constraints, possibly resulting in a more challenging task for participants. Their constrained task was layout design (furnish a room) while the open design task was "*propose and represent an outline design for a future personal entertainment system*" (Vieira et al., 2020a) using sketching. The varying level of constraints could have an influence on the observed differences in neurocognition and warrants further investigation.

4.3. Limitations

The results presented are based on an experiment design where task duration varies between participants, up to 10 minutes. The hemodynamic response plateaus after approximately 60 seconds, which means that our task duration is over the recommended maximum task duration in a block design. However, this plateau effect applies to all conditions, and we could argue that it cancels out when comparing conditions. Shealy et al. (2020) took a similar approach, calculating average HbO for tasks longer than 60 seconds. The time variation is a dimension warranting further investigation as average activation alone may not capture the nuances of participant engagement and cognitive processes during the experimental task. Time variation introduces an additional layer of complexity requiring consideration when interpreting results. Therefore, we take these results as an indication towards what the results after an analysis accounting for temporality (e.g., functional connectivity, a part of future work) would be.

4.4. Further work

Digital and physical prototyping tools and open and constrained processes influence brain activity. We found that physical prototyping led to increased brain activation in channels in the right PFC, which is consistent with prior research on creative thinking and divergent cognitive processes (Yi et al., 2022). This may suggest a potential link between the tangible, hands-on nature of physical prototyping and increased creative cognitive processes. However, the specific reasons underlying the observed increase in activation lateralizing to more channels in the right PFC during physical prototyping warrant further exploration. Better understanding the underlying mechanisms that drive these differences in neural activity can shed light on the cognitive processes triggered by physical prototyping. Future research could delve into the nuanced aspects of physical prototyping, such as the sensory feedback, motor engagement, or spatial exploration involved. The differences in stimuli (i.e., 2D visual versus full 3D visual plus tactile and auditory), direct tactile interaction with prototype rather than interaction via mouse and keyboard, familiarity with tools, and time pressure could all be contributing factors to the physical-digital difference. The additional constraints could increase designers stress during constrained design and time pressure could be contributing factors to the constrained-open difference. By unpacking these elements, we may attain a more comprehensive understanding of why physical prototyping elicits distinct patterns of cognitive activation compared to digital prototyping. To start addressing these speculations, future work will analyse the design outputs and design processes, and investigate their possible correlations with the fNIRS data. Significant differences in brain activation caused by physical and digital methods in prototyping leads us to ask the question of how increased digitisation impacts the types of design solutions we are creating. Studies of how digital communication affects brain activity (Balters et al., 2023b) support this further. It is therefore necessary to make evidenced decisions on how and why we decide to go digital when designing.

5. Conclusion

This article has presented result from an experiment investigating potential cognitive differences, as measured by fNIRS, between physical and digital prototyping in designers engaged in open and constrained design tasks. There appears to be a significant difference in hemodynamic activity in the PFC between physical and digital prototyping with physical prototyping yielding higher hemodynamic activity. There appears to be a significant difference between open and constrained design tasks, with constrained design tasks yielding higher hemodynamic activity in the PFC. These results are promising, warranting more sophisticated analysis methods and further research.

Data & code availability

Data and experiment code are publicly available at https://doi.org/10.17605/OSF.IO/YJR62. Analysis code and results are under \analysis\DESIGN2024.

Acknowledgements

The work in this article was funded by EPSRC projects 21st Century Prototyping (EP/W024152/1), The Development of the Physical-Digital Affordance Index (Researcher in Residence reference 142212012-2) and a University of Bristol Pump Priming grant.

References

Balters, S., Hawthorne, G., Reiss, A., 2023a. Priming Activity to Increase Interpersonal Closeness, Inter-brain Coherence, and Team Creativity Outcome.

Balters, S., Miller, J.G., Li, R., Hawthorne, G., Reiss, A.L., 2023b. Virtual (Zoom) Interactions Alter Conversational Behavior and Interbrain Coherence. J. Neurosci. 43, 2568–2578. https://doi.org/10.1523/JNEUROSCI.1401-22.2023

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. NPh 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, 289–300.

Donati, C., Vignoli, M., 2015. How tangible is your prototype? Designing the user and expert interaction. Int J Interact Des Manuf 9, 107–114. https://doi.org/10.1007/s12008-014-0232-5

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, 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

Goudswaard, M., Gopsill, J., Harvey, M., Snider, C., Bell, A., Hicks, B., 2021a. Revisiting Prototyping in 2020: A Snapshot of Practice in UK Design Companies. Proceedings of the Design Society 1, 2581–2590. https://doi.org/10.1017/pds.2021.519

Goudswaard, M., Snider, C., Gopsill, J., Jones, D., Harvey, M., Hicks, B., 2021b. The prototyping fungibility framework. Procedia CIRP, 31st CIRP Design Conference 2021 (CIRP Design 2021) 100, 271–276. https://doi.org/10.1016/j.procir.2021.05.066

Häggman, A., Tsai, G., Elsen, C., Honda, T., Yang, M.C., 2015. Connections Between the Design Tool, Design Attributes, and User Preferences in Early Stage Design. Journal of Mechanical Design 137. https://doi.org/10.1115/1.4030181

Hart, S.G., 2006. NASA-task load index (NASA-TLX); 20 years later. Presented at the Proceedings of the human factors and ergonomics society annual meeting, Sage Publications Sage CA: Los Angeles, CA, pp. 904–908.

Hernandez, S.M., Pollonini, L., 2020. NIRSplot: A Tool for Quality Assessment of fNIRS Scans, in: Biophotonics Congress: Biomedical Optics 2020 (Translational, Microscopy, OCT, OTS, BRAIN). Presented at the Optics and the Brain, OSA, Washington, DC, p. BM2C.5. https://doi.org/10.1364/BRAIN.2020.BM2C.5

Houde, S., Hill, C., 1997. What do prototypes prototype. Handbook of human-computer interaction 2, 367–381.

Hu, M., Shealy, T., Milovanovic, J., 2021. Cognitive differences among first-year and senior engineering students when generating design solutions with and without additional dimensions of sustainability. Design Science 7, e1. https://doi.org/10.1017/dsj.2021.3

Jacques, S.L., 2013. Optical properties of biological tissues: a review. Phys Med Biol 58, R37-61. https://doi.org/10.1088/0031-9155/58/11/R37

Jensen, M.B., 2017. Opportunities of Industry-Based Makerspaces: New Ways of Prototyping in the Fuzzy Front End.

Kent, L., Snider, C., Gopsill, J., Hicks, B., 2021. Mixed reality in design prototyping: A systematic review. Design Studies 77, 101046. https://doi.org/10.1016/j.destud.2021.101046

Leithner, C., Royl, G., 2014. The oxygen paradox of neurovascular coupling. J Cereb Blood Flow Metab 34, 19–29. https://doi.org/10.1038/jcbfm.2013.181

LeoCad, 2022. LeoCAD - a CAD application for creating virtual lego models.

Lim, Y.-K., Stolterman, E., Tenenberg, J., 2008. The anatomy of prototypes: Prototypes as filters, prototypes as manifestations of design ideas. ACM Transactions on Computer-Human Interaction (TOCHI) 15, 7.

Mathias, D., Hicks, B., Snider, C., Ranscombe, C., 2018. Characterising the Affordances and Limitations of Common Prototyping Techniques to Support The Early Stages of Product Development, in: DS 92: Proceedings of the DESIGN 2018 15th International Design Conference. Presented at the DESIGN 2018 - 15th International Design Conference, pp. 1257–1268. https://doi.org/10.21278/idc.2018.0445

McClenaghan, A., Goudswaard, M., Hicks, B., 2023. Investigating the Process, Design Outputs and Neurocognitive Differences between Prototyping Activities with Physical and Digital Lego, in: Proceedings of the International Conference on Engineering Design. Presented at the ICED23, Cambridge University Press, Bordeaux, France, pp. 2365–2374. https://doi.org/10.1017/pds.2023.237

Montero-Hernandez, S., Pollonini, L., 2022. QT-NIRS (Quality Testing of Near Infrared Scans).

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

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. Behav Res 51, 195–203. https://doi.org/10.3758/s13428-018-01193-y

Pinti, P., Tachtsidis, I., Hamilton, A., Hirsch, J., Aichelburg, C., Gilbert, S., Burgess, P.W., 2020. The present and future use of functional near-infrared spectroscopy (fNIRS) for cognitive neuroscience. Ann N Y Acad Sci 1464, 5–29. https://doi.org/10.1111/nyas.13948

Russel, J.A., Weiss, A., Mendelsohn, G.A., 1989. Affect grid: A single-item scale of pleasure and arousal. Journal of Personality and Social Psychology 57, 493–502.

Santosa, H., Zhai, X., Fishburn, F., Huppert, T., 2018. The NIRS Brain AnalyzIR Toolbox. Algorithms 11, 73. https://doi.org/10.3390/a11050073

Shealy, T., Gero, J., Hu, M., Milovanovic, J., 2020. Concept generation techniques change patterns of brain activation during engineering design. Design Science 6. https://doi.org/10.1017/dsj.2020.30

Vidulich, M.A., Tsang, P.S., 1987. Absolute Magnitude Estimation and Relative Judgement Approaches to Subjective Workload Assessment. Proceedings of the Human Factors Society Annual Meeting 31, 1057–1061. https://doi.org/10.1177/154193128703100930

Vieira, S., Gero, J.S., Delmoral, J., Gattol, V., Fernandes, C., Parente, M., Fernandes, A.A., 2020a. The neurophysiological activations of mechanical engineers and industrial designers while designing and problem-solving. Design Science 6. https://doi.org/10.1017/dsj.2020.26

Vieira, S., Gero, J.S., Delmoral, J., Li, S., Cascini, G., Fernandes, A., 2020b. Brain activity in constrained and open design spaces: an EEG study, in: Proceedings of the Sixth International Conference on Design Creativity (ICDC 2020). pp. 068–075.

Yi, K., Heo, J., Hong, J., Kim, C., 2022. The role of the right prefrontal cortex in the retrieval of weak representations. Sci Rep 12, 4537. https://doi.org/10.1038/s41598-022-08493-6

Zimeo Morais, G.A., Balardin, J.B., Sato, J.R., 2018. fNIRS Optodes' Location Decider (fOLD): a toolbox for probe arrangement guided by brain regions-of-interest. Scientific Reports 8, 3341. https://doi.org/10.1038/s41598-018-21716-z