# CHANGES IN COGNITION AND NEUROCOGNITION WHEN THINKING ALOUD DURING DESIGN

**Shealy, Tripp (1);**
**Gero, John (2);**
**Ignacio, Paulo (1);**
**Song, Inuk (1)**

1: Virginia Tech;
2: University of North Carolina at Charlotte.

## ABSTRACT

The think-aloud protocol provides researchers an insight into the designer's mental state, but little is understood about how thinking aloud influences design. The study presented in this paper sets out to measure the cognitive and neurocognitive changes in designers when thinking aloud. Engineering students (n=50) were randomly assigned to the think-aloud or control group. Students were outfitted with a functional near-infrared spectroscopy band. Students were asked to design a personal entertainment system. The think-aloud group spent significantly less time designing. Their design sketches included significantly fewer words. The think-aloud group also required significantly more resources in the left and right dorsolateral prefrontal cortex (DLPFC). The left DLPFC is often recruited for language processing, and the right DLPFC is involved in visual representation and problem-solving. The faster depletion of neurocognitive resources may have contributed to less time designing. Thinking aloud influences design cognition and neurocognition, but these effects are only now becoming apparent. More research and the adoption of neuroscience techniques can help shed light on these differences.

**Keywords**: Design cognition, Design methods, Design process, protocol analysis, fNIRS

**Contact**:
Shealy, Tripp
Virginia Tech
United States of America
tshealy@vt.edu

**Cite this article:** Shealy, T., Gero, J., Ignacio, P., Song, I. (2023) 'Changes in Cognition and Neurocognition When Thinking Aloud during Design', in *Proceedings of the International Conference on Engineering Design (ICED23),* Bordeaux, France, 24-28 July 2023. DOI:10.1017/pds.2023.87

## 1 INTRODUCTION

Thinking aloud is a commonly applied protocol in engineering design research. The process involves designers verbalizing what they think as they perform a task. Designers are asked to say what comes into their minds. This includes what they are looking at, thinking, doing, and feeling. It provides insight into the designer's mental state and cognitive processes.

Ericsson and Simon's (1980) seminal work on thinking aloud claims that this type of verbalization does not change cognition or mental states because the information is already being attended to by the designer. However, the influence of thinking aloud on design is still debated (Fox et al., 2011). Thinking aloud changes the perception of time (Hertzum and Holmegaard, 2015) and can delay the generation of ideas (Sun et al., 2021).

One explanation for why thinking aloud changes perceptions of time and delays idea generation is it increases designers' mental workload (Hertzum and Holmegaard, 2015). Mental workload is the number of cognitive resources required to perform a task or multiple tasks (Wickens, 2008). Mental workload is usually measured through task intensity (e.g., the number of tasks performed), using a psychological measure (e.g., a secondary task), or a subjective measure (e.g., a questionnaire) (Byrne, 2011). More recently, physiological measures (e.g., heart rate, skin conductivity, oxygenated hemoglobin) have been used to measure mental workload (Bunce et al., 2011; Midha et al., 2021; Peck et al., 2014).

One physiological measurement tool is functional near-infrared spectroscopy (fNIRS). fNIRS measures the change in oxygenated hemoglobin (oxy-Hb) in the human cortex. Increased oxy-Hb is a proxy for the increase in mental workload (Causse et al., 2017; Midha et al., 2021). Increased oxy-Hb correlates with self-reported NASA-TLX workload measures (Maior et al., 2014). The benefit of neuroimaging tools like fNIRS is the insight it provides into the patterns of activation in the brain when designing (Hu and Shealy, 2019; Shealy and Hu, 2017).

Mental workload is one possible explanation for the cognitive effect of thinking aloud when designing, but there are others. For example, thinking aloud may cause a shift in mental processing. That shift may overshadow the perception of time or require more attention, and this elicits the use of additional mental resources. fNIRS can test these hypotheses (Grohs et al., 2017; Jahani et al., 2017).

The study presented in this paper sets out to measure the neurocognitive changes in designers' brains when thinking aloud. The Background section provides an overview of studies measuring the effects of thinking aloud and outlines the use of fNIRS to study design neurocognition. The Methods section presents the experiment design approach to test the effects of thinking aloud on designers' neurocognition. The Results and Discussion sections offer new empirical evidence and detail how these findings relate to prior work. The Conclusion provides directions for future research.

## 2 BACKGROUND

Prior studies about the effects of thinking aloud when completing math problems (Pike et al., 2014) or riding a bike (Whitehead et al., 2022) suggest that thinking aloud does not impair performance. Yet, physiological changes do occur. The math task was more mentally demanding and required more cognitive effort, observable in the participants' brains (Pike et al., 2014). Thinking aloud when cycling reduced participants' heart rates leading to more efficient pacing efforts (Whitehead et al., 2022). Design is different from math and cycling. It involves imagining and planning the creation of objects and systems. The effects of thinking aloud on design neurocognition are not well understood.

Design requires the mental use of imagery and often elicits visuospatial reasoning (Bilda and Gero, 2005; Gero, 2015). Visuospatial reasoning requires activation in different brain regions. Verbalization uses the phonological loop, an area dedicated to working memory that temporarily holds verbal information (Pike et al., 2014). Verbalizing while eliciting visuospatial reasoning may require multi-tasking and additional cognitive effort.

This type of multi-tasking, designing while verbalizing, is characterized by the Multiple Resource Theory (Basil, 2012; Wickens, 2008), which asserts that people have a limited set of cognitive resources available for mental processing. These resources can be thought of as an energy bank. Resources are depleted with each mental operation. As these resources are allocated across different tasks, modalities, and processes, fewer resources are available. Cognitively demanding single-tasks can run into processing difficulties when too many resources are disbursed, and dual-task performance



https://doi.org/10.1017/pds.2023.87 Published online by Cambridge University Press

is more likely to be hampered when performing similar tasks than dissimilar tasks because of limitations in resource allocation to specific brain regions (Basil, 2012).

Multiple Resource Theory contends that the type of verbalization that occurs when thinking aloud matters. Ericsson and Simon (1993) distinguish three levels of verbalization when thinking aloud. Levels one and two involve the concurrent verbalization of information while executing a task. Level one is the task-relevant information, and level two includes any additional thoughts reflecting on the process. For example, a designer introducing a new design element is level one, and a designer expressing that they are running out of ideas to include in their design would be level two. Levels one and two are believed not to influence cognition because the designer is already thinking about it. Level three occurs when the designer explains their thought processes. Level three is the linking of information to earlier thoughts and information. For example, a designer makes a design choice and then explains why they made that decision before designing further. Level three verbalization is thought to direct attention and change the structure of the thought processes (Pike et al., 2014).

The level of verbalization often varies during thinking aloud (Hertzum et al., 2015). The objective of the protocol is to keep the designer talking, often with a simple prompt, such as "keep talking," to encourage the design participant to maintain verbalization about their thoughts and actions. Some prior studies use more directed questions (generally associated with level three verbalization), which involve asking participants for explanations, which can trigger redesign, evaluation, and even new ideas.

What designers say is believed to represent their thoughts but, as Ericsson and Simon (1993) attest, some types of verbalization (level three) may also change their thoughts. This change in thought is observable using instruments from neuroscience (Gero and Milovanovic, 2020). Functional magnetic resonance imaging (fMRI) provides high spatial resolution for the whole head but requires participants to lie down in a closed and confined space (Amaro and Barker, 2006). Electroencephalography (EEG) offers a very high temporal resolution compared to fMRI, but it is challenging to accurately pinpoint the brain region where electrical activity occurs (Burle et al., 2015). Functional near-infrared spectroscopy (fNIRS) offers aspects of both fMRI and EEG for design research, with relatively good resolution in space and time. A limitation of fNIRS is the measuring depth. It is limited to the human cortex (Strait and Scheutz, 2014). However, the prefrontal cortex, a key area for executive functions, is accessible and important for designing (Schneider et al., 2012).

fNIRS works by measuring the change in light reflection between a light source and a detector. This change in light reflection is caused by the changes in oxygenated (oxy-Hb) and deoxygenated (deoxy-Hb) hemoglobin in cortical brain regions. An increase in oxy-Hb typically mirrors more neuronal activity and implies the allocation of cognitive resources and nutrients by the cerebrovascular system (Csipo et al., 2021). fNIRS is often used to measure the change in neurocognition during tasks that require working memory (Lara and Wallis, 2015), attention, reasoning, and evaluations (Dietrich, 2004).

The prefrontal cortex (PFC) region of the brain is divided into multiple sub-regions, including the ventrolateral PFC (VLPFC), medial PFC (mPFC), dorsolateral PFC (DLPFC), and orbitofrontal cortex (OFC). These sub-regions contribute to different aspects of cognitive processing (Mihov et al., 2010; Shulman et al., 2010). For instance, the DLPFC is related to working memory and plays a key role in implementing functional connectivity between the language network and other functional networks (Curtis and D'Esposito, 2003; Hertrich et al., 2021). Activation in the DLPFC seems to be lateralized depending on the kind of information maintained. Depending on the task modality (e.g., auditory vs. visual), memory tasks engage different regions of the DLPFC (Rodriguez-Jimenez et al., 2009). The left DLPFC generally contains verbally coded content, overlapping with regions for language and speech generation (Buchsbaum and D'Esposito, 2008), and the right DLPFC more often contributes to a "visual sketchpad" for nonverbal content that is predominantly linked to visual representations (Baddeley, 2003). The mPFC is known to play a critical role in retrieving "remote" memories (Euston et al., 2012). The VLPFC was previously observed as a critical region for combining existing information into new ideas (Dietrich, 2004) and detecting similarity between items (Garcin et al., 2012).

Numerous methods exist to analyze fNIRS brain data (Hu and Shealy, 2019). The average change of oxy-Hb is a common approach (Hu and Shealy, 2019) and has been used in prior engineering design neurocognitive studies (Hu and Shealy, 2019; Milovanovic et al., 2021). For example, mean oxy-Hb has been used in measuring the effects of structured versus non-structured design techniques (Hu et al., 2018) and differences between first-year and fourth-year design students (Hu et al., 2021). This application of neuroimaging provides a new approach for measuring the effects of thinking aloud on design.



https://doi.org/10.1017/pds.2023.87 Published online by Cambridge University Press

## 3 RESEARCH QUESTION

The study in this paper attempts to answer the question: what is the effect of thinking aloud on design cognition and neurocognition? Insight into the effects of thinking aloud when designing on cognition and neurocognition can help design researchers objectively measure design.

## 4 METHODS

Undergraduate and graduate engineering students (n=50) were randomly assigned to the think-aloud or control group. Students in both groups were outfitted with an fNIRS headband. The fNIRS device used in this study was the OBELAB NIRSIT.

Before receiving the design instructions, students in the think-aloud group learned how to think aloud. A research team member demonstrated how to think aloud about an unrelated design task. Students were able to ask questions and were asked to practice using the same example question. They were to keep talking throughout the task and would be prompted if they were silent for too long.

Students sat at a desk with a display monitor and were given paper and a pencil. The monitor provided them with instructions about the task. Participants were first prompted to answer six multiplication problems with numbers ranging between one and ten. A new problem appeared every five seconds for a total of 30 seconds. The neurocognitive activation during this time was used as baseline data and later regressed out of the data (see the Pre-processing section for more detail).

Students were then prompted to design a personal entertainment system. They were given as much time as they needed. The monitor included instructions for the think-aloud group to think aloud while completing their design.

### 4.1 Pre-processing

The data collected from the fNIRS device is the change in optical density. The temporal derivative distribution repair (TDDR) motion correction was applied to the raw optical density data. A 1000th-order finite impulse response (FIR) bandpass filter with cut-offs between 0.01 – 0.25 Hz was then used to remove artifacts from respiration (0.2 – 0.6 Hz). The modified Beer-Lambert law to get hemoglobin concentration was then applied. This process is illustrated in Figure 1.

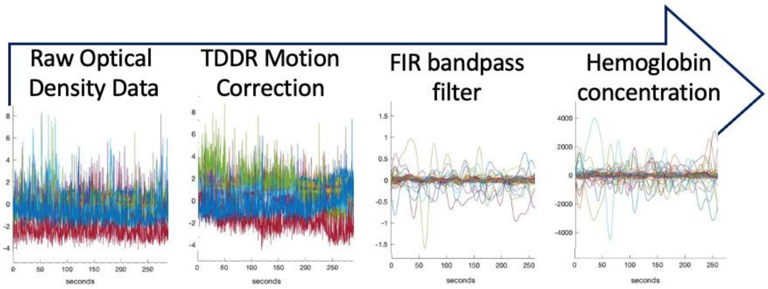


*Figure 1: fNIRS data pre-processing procedure*

### 4.2 Analysis

Physiological artifacts from cardiac pulsation (0.6-2.5 Hz) and the Mayer wave caused by blood pressure (0.1 Hz) remained in the data. This was regressed using the median time series data of the 15 mm, short-channel activation from the 30 mm activation. The 15 mm detector from the source penetrates the scalp and skull but not the cortex. Regressing this data removed physiological artifacts and the Mayer wave leaving the changes in hemoglobin elicited by the task stimuli.

The mean difference in oxy-Hb between groups was compared for each region illustrated in Figure 2. The broad region of interest was the prefrontal cortex (PFC) because of its role in executive functions. The regions include the ventrolateral, dorsolateral, frontopolar, and orbitofrontal cortex. The mean oxy-Hb across the entire design process and the first and second half of the design were compared. The data were split into halves to account for changes in time. The data were not normally distributed, so the Mann-Whitney U Test, instead of an independent t-test, was used to compare the mean oxy-Hb in each of the prefrontal cortex regions. The confidence interval was 0.05. Outliers more than two standard deviations from the mean were also removed from the analysis.



https://doi.org/10.1017/pds.2023.87 Published online by Cambridge University Press

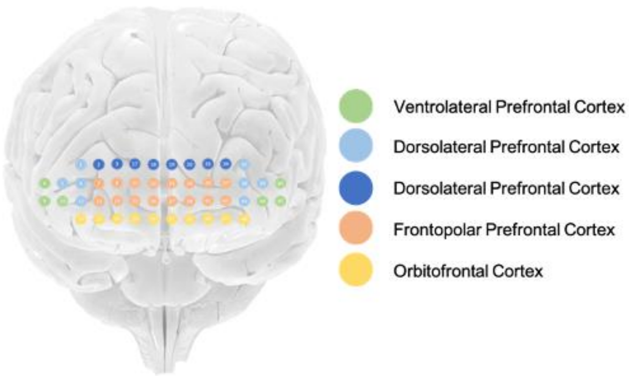


*Figure 2: Channel configuration along the prefrontal cortex for OBELAB fNIRS.*

### 4.3 Task data

The time to complete the design task and the design sketches were used to compare differences between groups. After checking for normal distribution of the length of time participants spent designing, an independent t-test was used to compare differences between the think-aloud and control groups. The confidence interval was 0.05. The number of words included in students' design sketches was also compared between groups. The number of words on each design sketch was counted, and normal distribution was checked for each group and then compared using a Mann-Whitney U Test because the data were non-normally distributed. The confidence interval was 0.05.

In addition, the audio recordings from students in the think-aloud group were transcribed. Common words were removed. The number of first-occurrence words, or unique words, used when thinking aloud was counted. The number of words included on drawings and verbalized was compared for the think-aloud group using Wilcoxon Rank Sum Test, similar to a paired t-test used for non-parametric data. The number of verbalized first-occurrence words was added to the total number used to describe each sketch. Normal distribution was checked again, and a Mann-Whitney U Test was used to compare each group's total number of descriptor words because of non-normally distributed data.

## 5 RESULTS

The time to complete the design task was significantly different between groups. The control group spent more time designing (mean = 590 seconds (9.8 minutes), STD = 316 seconds) ($t = 2.94$, $p = 0.005$) compared to the think-aloud group (mean = 348 seconds (5.8 minutes), STD = 183 seconds). This is illustrated in Figure 3.

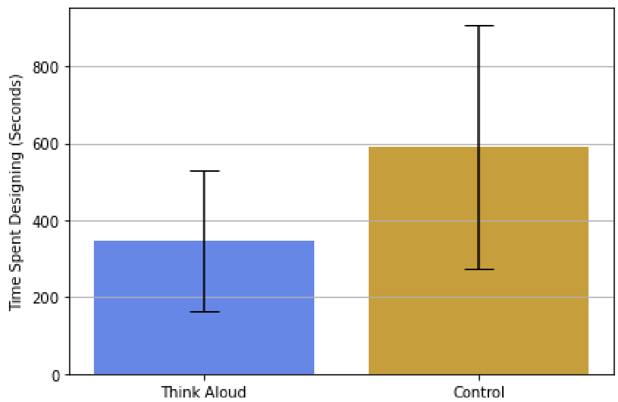


*Figure 3: The think-aloud group spent significantly less time designing compared to the control group.*

The design sketches produced by the control group included significantly more words (statistic = 203, $p = 0.05$) than the think-aloud group. The average number of words from the control group was 31.7, but with large variability between participants (standard deviation was 34.4 words). The average


https://doi.org/10.1017/pds.2023.87 Published online by Cambridge University Press

number of words from the think-aloud group was 14.9, with a standard deviation of 20.2. Figure 4 includes an example design drawing from students in each group.

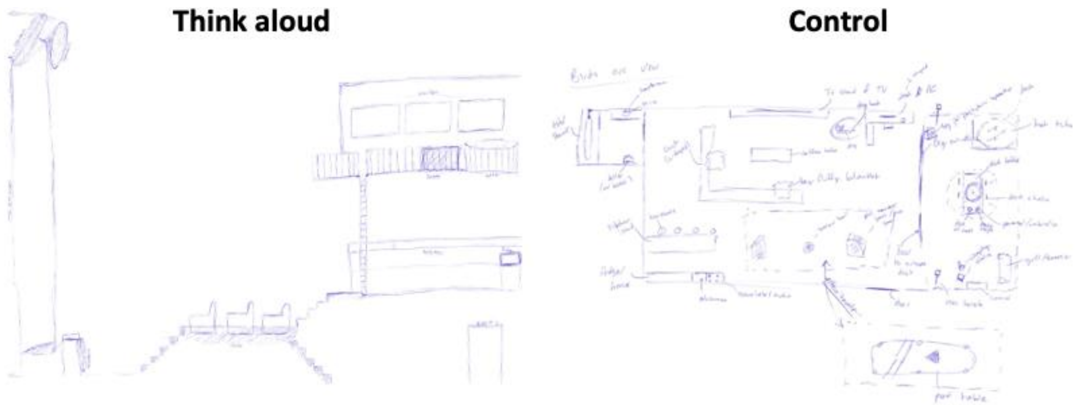


*Figure 4: Example design drawings from students in the think-aloud and control group*

The total number of words used to describe design ideas increased significantly ($p < 0.001$) for the think-aloud group from 14.9 words (standard deviation = 20.2) to 127.75 words (standard deviation = 88.3) when first occurrence words were added. The total number of combined words verbalized and written, to describe their design ideas for the think-aloud group was significantly more (statistic = 532.5, $p < 0.001$) compared to the number of words written by the control group. The think-aloud group used nearly four times as many descriptive words.

Neurocognitive differences were also observed in sub-regions of the left and right dorsolateral prefrontal cortex. Differences in the right dorsolateral prefrontal cortex (PFC) were observed in Channel 2 (statistic=303, $p = 0.016$) and Channel 3 (statistic=316, $p = 0.006$), and in the left dorsolateral PFC, in Channel 35 (statistic=300, $p = 0.02$) (see Figure 2 for channel numbering). In all three channels, the think-aloud group elicited significantly greater mean oxy-Hb than the control. The patterns of neurocognitive activation in the PFC when designing between the two groups are illustrated in Figure 5. The circles in the Figure highlight the channel differences that were significant. A notable increase in oxy-Hb is also observed in the think-aloud group in the right orbitofrontal cortex, Channel 15. The difference in this channel was not significant (statistic=253, $p = 0.27$) across the entire design due to the large variance observed within the control group. However, differences in oxy-Hb were significantly greater in the think-aloud group during the second half of the design process (statistic=286, $p = 0.05$). In other words, the think-aloud group also elicited more oxy-Hb in the right orbitofrontal cortex in the second half of the design process.

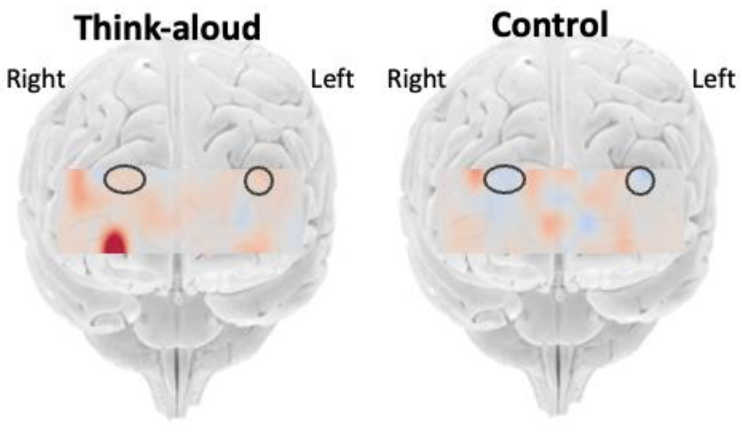


*Figure 5: Brain activation while designing. Red indicates elevated levels of oxygenated hemoglobin (oxy-Hb), and blue indicates a decrease in oxy-Hb. The circles indicated the region with significantly different levels of oxy-Hb in channels representing the right and left dorsolateral prefrontal cortex between the think-aloud and control groups.*



https://doi.org/10.1017/pds.2023.87 Published online by Cambridge University Press

## 6 DISCUSSION

Design students who were asked to think aloud spent significantly less time designing. They also included significantly fewer words in their design sketches. Less time designing and fewer descriptive words provide fewer observable data about students' design cognition and implies that thinking aloud negatively contributes to designing. However, when the words they verbalized were added to the words included in their sketches, the cumulative descriptions were significantly more than the control group – close to four times as many descriptive words. Thinking aloud changed how students communicated their designs and the time spent designing.

Thinking aloud also led to a significant change in brain behavior. Thinking aloud altered brain behavior in the left and right dorsolateral prefrontal cortex throughout the design process and, as time progressed, also in the right orbitofrontal cortex. The DLPFC is often considered part of the "multiple demand system" (Hertrich et al., 2021), meaning activation in this region is observed with multiple cognitive tasks involving executive functions. It is known to play a role in the creative thinking process (Mihov et al., 2010), relational memory encoding (Blumenfeld et al., 2011), concept generation (Milovanovic et al., 2020; Shealy et al., 2017), task-relevant representations (Mars and Grol, 2007), and decision-making (Jamali et al., 2019). Hemispherical differences in the left and right DLPFC are often associated with different cognitive functions. For example, intuitive ideas are often associated with increased activation in the right DLPFC (Pisapia et al., 2016). The right DLPFC also plays a role when solving ill-structured design problems (Alexiou et al., 2011). The left DLPFC is often recruited for language-processing tasks (Hertrich et al., 2021).

The increased brain activation in the left DLPFC corresponds with its role in the language processing (Hertrich et al., 2021). The increased activation in the right DLPFC may also be a result of the continued verbalization that occurs when thinking aloud. Design ideas generally peak early in the design process and decay over time (Viswanathan, 2017). As the design progressed, designers that were required to continue verbalizing their ideas had to work harder to develop new ideas to continue to verbalize aloud, and this increase in the production of ideas may be represented by the increased activation in the right DLPFC. This aligns with prior research findings that found an increase in activation in the right DLPFC corresponded with an increase in the number of design ideas engineering students generated (Hu, 2018).

The right orbitofrontal cortex was the other region that was observed to increase in activation. This region is often associated with decision-making (Rolls et al., 2020). A possible explanation for this increase in activation is that thinking aloud required some level of judgment and decision-making about what to say and include in their design, which resulted in a build-up of oxy-Hb in this region over time.

These observed changes in brain behavior point to an explanation of why thinking aloud led to a significant reduction in design time but more design ideas. The faster depletion of neurocognitive resources may have contributed to significantly less time designing. Designers in the think-aloud group said more and consumed more neurocognitive resources, indicated by the increase in oxy-Hb. Multi-Resource Theory asserts that the dual-task performance of designing and thinking aloud should not impede each other because verbalization and visuospatial reasoning occur in different portions of the brain (Basil, 2012; Wickens, 2008). Yet, the findings presented in this paper suggest a neurocognitive and cognitive effect. As more cognitive resources were consumed in the left and right DLPFC and right orbitofrontal cortex, fewer resources were available to complete both tasks. This led to a reduction in the time spent designing and an increase in the description of their design ideas.

## 7 CONCLUSION

Cognitive and neurocognitive differences during design were observed between students who were required to think aloud and those who were not asked to think aloud. Students thinking aloud spent less time designing, included fewer words in their design sketches, and consumed more neurocognitive resources during the design process, specifically in the left and right dorsolateral prefrontal cortex. This region of the prefrontal cortex is often associated with idea generation and language processing. The consumption of additional neurocognitive resources led to significantly greater verbalized words than those included in the design sketches from the control group. Thinking aloud while designing produces more than just a verbal description of design elements; it includes insight into the designer's thought processes. The results from this study suggest that this type of


https://doi.org/10.1017/pds.2023.87 Published online by Cambridge University Press

verbalization changes designers' brain behavior, eliciting an increase in neurocognitive resources, specifically in the regions of the brain often associated with language processing, idea production, and decision-making.

Further research about the cognitive and neurocognitive effects of thinking aloud is needed. Mean oxy-Hb is only one measure of brain activation. The functional connectivity of brain regions, in other words, how regions function together, should be explored to understand how patterns of activation relate to one another. The temporal effects of thinking aloud also need more investigation. Differences were observed later in the design process, specifically in the right orbitofrontal cortex, a region often associated with making judgments and decisions, and this increased demand for neurocognitive resources both in the DLPFC and orbitofrontal cortex may have contributed to the significantly less time spent designing. Thinking aloud does influence design cognition and neurocognition, but these effects are only now becoming apparent. More research and the adoption of tools and techniques from neuroscience can help shed new light on these differences.

## ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under Grant Nos. 1929892, 1929896, 2128039 and 2128026. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

## REFERENCES

Alexiou, K., Zamenopoulos, T., Gilbert, S. (2011), "Imaging the Designing Brain: A Neurocognitive Exploration of Design Thinking", *Design Computing and Cognition*. Springer Netherlands, pp. 489–504. https://doi.org/10.1007/978-94-007-0510-4_26

Amaro, E., Barker, G.J. (2006), "Study design in fMRI: Basic principles", *Brain and Cognition* Vol. 60, pp. 220–232. https://doi.org/10.1016/j.bandc.2005.11.009

Baddeley, A. (2003), "Working memory: looking back and looking forward", *Nature Reviews Neuroscience* Vol. 4, pp. 829–839. https://doi.org/10.1038/nrn1201

Basil, M.D. (2012), "Multiple Resource Theory", *Encyclopedia of the Sciences of Learning*. Springer US, Boston, MA, pp. 2384–2385. https://doi.org/10.1007/978-1-4419-1428-6_25

Bilda, Z., Gero, J.S. (2005), "Does sketching off-load visuo-spatial working memory", *Studying designers*, Sydney, Australia, pp. 145–160. Available at: https://cs.gmu.edu/~jgero/publications/2005/05BildaGeroSD05.pdf (Accessed: 20 April 2021)

Blumenfeld, R.S., Parks, C.M., Yonelinas, A.P., Ranganath, C. (2011), "Putting the pieces together: The role of dorsolateral prefrontal cortex in relational memory encoding", *Journal of Cognitive Neuroscience* Vol. 23, pp. 257–265. https://doi.org/10.1162/jocn.2010.21459

Buchsbaum, B.R., D'Esposito, M. (2008), "The search for the phonological store: From loop to convolution", *Journal of Cognitive Neuroscience* Vol. 20, pp. 762–778. https://doi.org/10.1162/jocn.2008.20501

Bunce, S.C., Izzetoglu, K., Ayaz, H., Shewokis, P., Izzetoglu, M., Pourrezaei, K., Onaral, B. (2011), "Implementation of fNIRS for Monitoring Levels of Expertise and Mental Workload", *Foundations of Augmented Cognition*, Springer Berlin Heidelberg, pp. 13–22. https://doi.org/10.1007/978-3-642-21852-1_2

Burle, B., Spieser, L., Roger, C., Casini, L., Hasbroucq, T., Vidal, F. (2015), "Spatial and temporal resolutions of EEG: Is it really black and white? A scalp current density view", *International Journal of Psychophysiology* Vol. 97, pp. 210–220. https://doi.org/10.1016/j.ijpsycho.2015.05.004

Byrne, A. (2011), "Measurement of Mental Workload in Clinical Medicine: A Review Study", *Anesthesia and Pain Medicine* Vol. 1, pp. 90–94. https://doi.org/10.5812/kowsar.22287523.2045

Causse, M., Chua, Z., Peysakhovich, V., Campo, N.D., Matton, N. (2017), "Mental workload and neural efficiency quantified in the prefrontal cortex using fNIRS", *Scientific Reports* Vol. 7, pp. 1–15. https://doi.org/10.1038/s41598-017-05378-x

Csipo, T., Lipecz, A., Mukli, P., Bahadli, D., Abdulhussein, O., Owens, C.D., Tarantini, S., Hand, R.A., Yabluchanska, V., Kellawan, J.M., Sorond, F., James, J.A., Csiszar, A., Ungvari, Z.I., Yabluchanskiy, A. (2021), "Increased cognitive workload evokes greater neurovascular coupling responses in healthy young adults", *PLOS ONE* Vol. 16, e0250043. https://doi.org/10.1371/journal.pone.0250043

Curtis, C.E., D'Esposito, M. (2003), "Persistent activity in the prefrontal cortex during working memory", *Trends in Cognitive Sciences* Vol. 7, pp. 415–423.

Dietrich, A. (2004), "The cognitive neuroscience of creativity", *Psychonomic Bulletin & Review* Vol. 11, pp. 1011–1026. https://doi.org/10.3758/BF03196731

Ericsson, K.A., Simon, H.A. (1993), "Protocol analysis: Verbal reports as data", *Protocol analysis: Verbal reports as data*, The MIT Press, Cambridge, MA, US.

Ericsson, K.A., Simon, H.A. (1980), "Verbal reports as data". *Psychological Review* Vol. 87, pp. 215–251. https://doi.org/10.1037/0033-295X.87.3.215
Euston, D.R., Gruber, A.J., McNaughton, B.L. (2012), "The Role of Medial Prefrontal Cortex in Memory and Decision Making", *Neuron* Vol. 76, 1057–1070. https://doi.org/10.1016/j.neuron.2012.12.002
Fox, M.C., Ericsson, K.A., Best, R. (2011), "Do procedures for verbal reporting of thinking have to be reactive? A meta-analysis and recommendations for best reporting methods", *Psychological Bulletin* Vol. 137, pp. 316–344. https://doi.org/10.1037/a0021663
Garcin, B., Volle, E., Dubois, B., Levy, R. (2012), "Similar or Different? The Role of the Ventrolateral Prefrontal Cortex in Similarity Detection", *PLOS ONE* Vol. 7, e34164. https://doi.org/10.1371/journal.pone.0034164
Gero, J.S. (2015), *Studying Visual and Spatial Reasoning for Design Creativity*, Springer Netherlands, Dordrecht.
Gero, J.S., Milovanovic, J. (2020), "A framework for studying design thinking through measuring designers' minds, bodies and brains", *Design Science* Vol. 6. https://doi.org/10.1017/dsj.2020.15
Grohs, J., Shealy, T., Maczka, D., Hu, M. (2017), "Evaluating the Potential of fNIRS Neuroimaging to Study Engineering Problem Solving and Design", ASCE, Columbus, OH. Available at: https://peer.asee.org/evaluating-the-potential-of-fnirs-neuroimaging-to-study-engineering-problem-solving-and-design (Accessed: 06 May 2021)
Hertrich, I., Dietrich, S., Blum, C., Ackermann, H. (2021), "The Role of the Dorsolateral Prefrontal Cortex for Speech and Language Processing", *Frontiers in Human Neuroscience* Vol. 15.
Hertzum, M., Borlund, P., Kristoffersen, K.B. (2015), "What Do Thinking-Aloud Participants Say? A Comparison of Moderated and Unmoderated Usability Sessions", *International Journal of Human–Computer Interaction* Vol. 31, pp. 557–570. https://doi.org/10.1080/10447318.2015.1065691
Hertzum, M., Holmegaard, K.D. (2015), "Thinking Aloud Influences Perceived Time", *Human Factors* Vol. 57, pp. 101–109. https://doi.org/10.1177/0018720814540208
Hu, M., 2018. *Neuroscience for Engineering Sustainability: Measuring Cognition During Design Ideation and Systems Thinking Among Students in Engineering* (Thesis). Virginia Tech.
Hu, M., Shealy, T. (2019), "Application of Functional Near-Infrared Spectroscopy to Measure Engineering Decision-Making and Design Cognition: Literature Review and Synthesis of Methods", *Journal of Computing in Civil Engineering* Vol. 33, 04019034. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000848
Hu, M., Shealy, T., Gero, J.S. (2018), "Neuro-cognitive Differences Among Engineering Students when Using Unstructured, Partially Structured, and Structured Design Concept Generation Techniques", *ASEE Annual Conference & Exposition*.
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* Vol. 7. https://doi.org/10.1017/dsj.2021.3
Jahani, S., Fantana, A.L., Harper, D., Ellison, J.M., Boas, D.A., Forester, B.P., Yücel, M.A. (2017), "fNIRS can robustly measure brain activity during memory encoding and retrieval in healthy subjects", *Scientific Reports* Vol. 7. https://doi.org/10.1038/s41598-017-09868-w
Jamali, M., Grannan, B., Haroush, K., Moses, Z.B., Eskandar, E.N., Herrington, T., Patel, S., Williams, Z.M. (2019), "Dorsolateral prefrontal neurons mediate subjective decisions and their variation in humans", *Nature Neuroscience* Vol. 22, pp. 1010–1020. https://doi.org/10.1038/s41593-019-0378-3
Lara, A.H., Wallis, J.D. (2015), "The Role of Prefrontal Cortex in Working Memory: A Mini Review." *Frontiers in Systems Neuroscience* Vol. 9, pp. 173. https://doi.org/10.3389/fnsys.2015.00173
Maior, H.A., Pike, M., Wilson, M.L., Sharples, S. (2014), "Continuous detection of workload overload: An fnirs approach", *Contemporary Ergonomics and Human Factors* Vol. 450.
Mars, R.B., Grol, M.J. (2007), "Dorsolateral Prefrontal Cortex, Working Memory, and Prospective Coding for Action", *Journal of Neuroscience* Vol. 27, pp. 1801–1802. https://doi.org/10.1523/JNEUROSCI.5344-06.2007
Midha, S., Maior, H.A., Wilson, M.L., Sharples, S. (2021), "Measuring Mental Workload Variations in Office Work Tasks using fNIRS", *International Journal of Human-Computer Studies*, Vol. 147, 102580. https://doi.org/10.1016/j.ijhcs.2020.102580
Mihov, K.M., Denzler, M., Förster, J. (2010), "Hemispheric specialization and creative thinking: A meta-analytic review of lateralization of creativity", *Brain and Cognition*, Vol. 72, pp. 442–448. https://doi.org/10.1016/j.bandc.2009.12.007
Milovanovic, J., Hu, M., Shealy, T., Gero, J. (2021), "Characterization of concept generation for engineering design through temporal brain network analysis", *Design Studies*, Vol. 76, 101044. https://doi.org/10.1016/j.destud.2021.101044
Milovanovic, J., Hu, M., Shealy, T., Gero, J. (2020), "Evolution of Brain Network Connectivity in the Prefrontal Cortex During Concept Generation Using Brainstorming for a Design Task", *ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, American Society of Mechanical Engineers Digital Collection. https://doi.org/10.1115/DETC2020-22563

Peck, E.M., Afergan, D., Yuksel, B.F., Lalooses, F., Jacob, R.J.K. (2014), "Using fNIRS to Measure Mental Workload in the Real World", *Advances in Physiological Computing, Human–Computer Interaction Series*. Springer, London, pp. 117–139. https://doi.org/10.1007/978-1-4471-6392-3_6

Pike, M.F., Maior, H.A., Porcheron, M., Sharples, S.C., Wilson, M.L. (2014), "Measuring the Effect of Think Aloud Protocols on Workload Using fNIRS", *SIGCHI Conference on Human Factors in Computing Systems*, ACM, New York, NY, USA, pp. 3807–3816. https://doi.org/10.1145/2556288.2556974

Pisapia, N.D., Bacci, F., Parrott, D., Melcher, D. (2016), "Brain networks for visual creativity: a functional connectivity study of planning a visual artwork", *Scientific Reports*, Vol. 6, 39185. https://doi.org/10.1038/srep39185

Rodriguez-Jimenez, R., Avila, C., Garcia-Navarro, C., Bagney, A., de Aragon, A.M., Ventura-Campos, N., Martinez-Gras, I., Forn, C., Ponce, G., Rubio, G., Jimenez-Arriero, M.A., Palomo, T. (2009), "Differential dorsolateral prefrontal cortex activation during a verbal n-back task according to sensory modality," *Behavioural Brain Research* Vol. 205, pp. 299–302. https://doi.org/10.1016/j.bbr.2009.08.022

Rolls, E.T., Cheng, W., Feng, J. (2020), "The orbitofrontal cortex: reward, emotion and depression", *Brain Communications* Vol. 2, fcaa196. https://doi.org/10.1093/braincomms/fcaa196

Schneider, W.X., Owen, A.M., Duncan, J. (2012) *Executive Control and the Frontal Lobe: Current Issues*, Springer, Berlin, Heidelberg.

Shealy, T., Grohs, J., Hu, M., Maczka, D., Panneton, R. (2017), "Investigating Design Cognition during Brainstorming Tasks with Freshmen and Senior Engineering Students using Functional Near Infrared Spectroscopy", *ASEE Annual Conference*, Columbus, OH.

Shealy, T., Hu, M. (2017), "Evaluating the potential of neuroimaging methods to study engineering cognition and project-level decision making", *EPOC-MW Conference*, Engineering Project Organization Society, Fallen Leaf Lake, CA.

Shulman, G.L., Pope, D.L.W., Astafiev, S.V., McAvoy, M.P., Snyder, A.Z., Corbetta, M. (2010), "Right Hemisphere Dominance during Spatial Selective Attention and Target Detection Occurs Outside the Dorsal Frontoparietal Network", *Journal of Neuroscience*, Vol. 30, pp. 3640–3651. https://doi.org/10.1523/JNEUROSCI.4085-09.2010

Strait, M., Scheutz, M. (2014), "What we can and cannot (yet) do with functional near infrared spectroscopy", *Frontiers in Neuroscience* Vol. 8. https://doi.org/10.3389/fnins.2014.00117

Sun, S., Li, T., Zhou, X. (2021), "Effects of thinking aloud on cognitive effort in translation", *Linguistica Antverpiensia*, New Series – Themes in Translation Studies Vol. 19.

Viswanathan, V.K. (2017), "Design fixation to examples: A study on the time decay of fixation", P*roceedings of the 21st International Conference on Engineering Design (ICED 17)*, Vol 8, Vancouver, Canada, 21-25.08.2017.

Whitehead, A., Montgomery, C., Swettenham, L., Robinson, N.J. (2022), "The Effect of Think Aloud on Performance and Brain Oxygenation During Cycling – An Exploratory Study", *Perception Motor Skills*, Vol. 129, 1115–1136. https://doi.org/10.1177/00315125221104769

Wickens, C.D. (2008), "Multiple Resources and Mental Workload", *Human Factors*, Vol. 50, pp. 449–455. https://doi.org/10.1518/001872008X288394