Towards Instantiating Design 
Principles for Physical Networks

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ABSTRACT
This paper proposes a methodology towards auto-generating physicalizations based on our experience developing node-link network physicalizations. Within the first stage of the methodology, identifying physical characteristics, we discuss how design principles applied in visualization can be adapted to the field of Data Physicalization and Multisensory Immersive Analytics. Subsequently, we identify features that could be implemented into theoretical physicalization software for instantiating physical characteristics into a potential representation of data. Finally, we discuss evaluation of the physical characteristics from instantiation, to determine if the representation affects perception and cognition of the data. We conclude with suggestions for future work.

KEYWORDS
multisensory, immersive analytics, physicalization, networks, graphs

INTRODUCTION
In this paper, we discuss the potential for Data Physicalization, under the umbrella of Multisensory Immersive Analytics, towards the development of tools designers can use to generate physicalizations. Based on our experience from iterating the design of several node-link network physicalizations, we propose a methodology adapted from Argawala’s [1] work on visual communication that broadly encapsulates a methodology of generating physicalizations and tangibles.
Our three-stage methodology involves the designer first identifying physical characteristics they want to incorporate into their design. Before either developing or autonomously generating a physicalization, a designer must understand the prescriptive rules that they would like to be embodied within their physicalization. Commonly in graphic design and information visualization, a designer will first analyze the best “hand-designed” visualizations and pick specific characteristics that they would like to incorporate within their design. This is also the case in modern information visualization tools, as users working with software will often experiment with different tools to try to match other well-crafted examples. In contrast, a majority of network physicalizations come from the art world and mainly focus on aesthetics and invoking emotion. In this paper, we discuss examining examples of physicalizations derived from the arts in context to White’s principles of design [22] as a means for a designer to extract characteristics for a potential physicalization.

The second stage in the methodology is the instantiation of the physical characteristics. This stage involves the designer developing a physicalization based on the identified design principles and characteristics they want to embed into their representation. Our interest into instantiation is twofold; first, can tools be developed to automate the process of creating these physicalizations; second, is possible to replicate the aesthetics that come with hand-crafted physicalizations with perception and cognition in mind. In addition, we discuss potential features to be added to engage with non-visual senses. In this paper, we present some of our work towards automating the process of creating physicalizations through examples we developed (see Figure 1).

The final stage, evaluation, focuses on evaluating the physical characteristics so that designers can determine how effective their physicalizations are upon perception and cognition for the intended domain. After discussing the three stages, we conclude with future directions.

RELATED WORK

Multisensory Immersive Analytics (MIA)

Multisensory Immersive Analytics (MIA) [6, 13] is an emerging area of research involving the study of using all of our senses to perceive and interact with information. MIA encourages multimodality [15], which affords information to be perceived from bodily interpreters outside of the eyes, embracing the use of ears, nose, mouth, and skin.

Data Physicalization

Data Physicalization [11] is the study of physical representations of data, known as physicalizations. Physicalizations can make data more perceptive and memorable by engaging people through non-visual senses such as texture, stiffness, temperature, and weight. Data Physicalization is a integral
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part of MIA emphasising on information perception from skin receptors including mechanoreceptors, proprioceptors, thermoreceptors, and nociceptors. Mechanoreceptors give people perception of indentation and vibration on surfaces. Proprioceptors allow people to perceive their own muscles and body position. Thermoreceptors enable perception of temperature in an environment or on a physical surface. Nociceptors allow people to detect pain and attempt to protect the body from harm. When designing a physicalization or tangible object, it is important to address that bodily receptors can in fact be used as a design tool. In this paper, we shall address how to approach using receptors as a design tool through physicalization examples and prospective scenarios.

Embodied Cognition
Embodied cognition is an area of research investigating how our experiences occurring in the physical world can influence human thought. For example, William et al. [23] found that participants who held a warm cup of coffee opposed to a cold cup judge an individual as trustworthy as opposed to not. Slepian et al. [17] found that participants perceived a gender neutral face as female if a rubber ball was soft and male if the ball was rough. Jostmann et al. [5] found that participants who held a light clipboard in constrast to a heavy clipboard perceived a meeting as less important than participants with a heavy clipboard. We are interested in if through embodied cognition, our bodily experiences can affect perception and cognition of data, such as creating more memorable, comprehensive, perceptions of data (See Figure 2).

Tactile Graphics
Tactile Graphics [14] is a medium of information representation that enables visually-impaired individuals to interpret graphics such as diagrams and illustrations on raised surfaces through touch. Tactile Graphics are widely applied to convey spatial relationships [8, 10, 16] through textural information (see Figure 3).

METHODOLOGY
Influenced by Argawala’s [1] work on visual communication, we outline a three-step methodology for generating physicalizations and tangibles. The three-stage methodology involves first identifying physical characteristics to be incorporated into the design, followed by instantiation of those characteristics, then evaluation of the physical characteristics. We discuss the three stages below in detail.

Identifying
Fundamentally, when designing a visualization, a designer will consciously or unconsciously embed principles of design within their work. White [22] discusses design principles in terms of graphic
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design, but they are universal across information visualization and data physicalization. These design principles include unity, gestalt, space, dominance, hierarchy, balance and colour. Physical characteristics concern what characteristics are embodied within the output representation, which are extracted and discovered by following design principles. We discuss thinking about design principles below, and leverage them to discuss potential physical characteristics that can be encoded within a data representation.

Unity: The first design principle unity concerns how all the elements within a visualization appear to belong together. In the context of network visualization, the groundwork of unity largely derives from the layout algorithm. A layout algorithm will ideally place all the nodes in a space such that the network is legible and relationships between nodes can be understood. Without a layout algorithm, unity is broken with problems identified by Ware et al. [21] arising such as edge crossings, lack of symmetry, and bends in edges. With physicalizing networks, unity can be supported visually with a layout algorithm but the problem emerges of when unity can become affected by gravity. Ideally when laying out a physical network, it needs to take into account the space it will be used in, and how people will interact with it, introducing the problem of physical unity. Dehmamy et al. [4] investigated laying out physical networks, and suggest that structurally laying out the network to avoid edge crossing and minimizing edges increases the amount of tensile strength to avoid breakage. Thus, with this in mind, physical networks can become more tangible, eliciting strength as important factor of physicalization. We additionally looked into increasing tensile strength for network physicalizations, finding using flexible materials to be a promising approach to decreasing fragility (see Figure 4).

Gestalt: The next design principle, gestalt, also concerns wholeness, covering closure and continuation, and figure-ground. Closure and continuation is necessary for perceiving relationships in a representation and contrasting between different elements, which are standard in visualization. Figure-ground however presents a new set of challenges for physicalization. Figure-ground involves how the subject (physicalization) relates to the surrounding space. Ideally, a physicalization should visually and physically stand out from the space its present in. For example, a physicalization should not be the same material and same colour as the desk it resides on to avoid confusion. Oliver Bieh-Zimmert’s physicalization “Network of the German Civil Code” [2] uses figure-ground well by using the colour red to contrast against the wall its displayed on.

Space: Figure-ground closely relates to space, which is the consideration of negative space in relation to unity, gestalt, and other design principles. In the context of multisensory immersive analytics, space elicits the potential of using properties of physical space to contrast between figure-ground. For example, considering olfactory, sound, temperature of a physical space in contrast to the physicalization to affect a person’s perception of the data (see Figure 5, 6).

Dominance: Consequently, the next design principle dominance involves the contrast between one element to another. Klemm and Ernesto [12] used clusters of balloons in a physicalization to
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Conveying CO₂ emissions around the world, which clearly translates countries dominating each other in CO₂ emissions. Klemm and Ernesto’s work used size to convey dominance, however there are other approaches in the design space of physicalization that could be utilized. In a tangible sense, parts of a physicalization could contrast by considering the different receptors such as mecanoreceptors, proprioceptors, thermoreceptors, and nociceptors. Through the use of thermoreceptors, elements of a network could be colder or hotter, thus affecting one’s perception of the data. In that context, hotter elements in a network could represent entities that are more polluted, and colder elements could represent entities that are less polluted. Herman and Keefe [9] investigated using varying physical glyphs on spheres such that data could be interpreted by mecanoreceptors. For example, when holding a different sphere in either hand, one could tell the difference haptically through texture rather than visually.

Figure 5: Conceptual interface for swiping through different sensory options to manipulate a physicalization’s properties, such as temperature, olfactory, sound, and sight.

Figure 6: Making a physicalization contrast or alike to its surrounding temperature before instantiation.

**Hierarchy**: Following dominance, hierarchy concerns proximity and similarity between the elements of the representation. The goal of hierarchy is to place elements that are of importance close, and elements that are less important far, in relation to an element. In the case of network physicalization, entities that are alike should be in close proximity to each other in a physical space. Data Streamer’s Data String Installation [19] uses proximity well by vertically mapping age and social status on physical parallel plots which helps separate unlike data points and group alike data points. For similarity, entities that are similar should have related physical properties, in respect to texture, stiffness, temperature and weight to improve readability through receptors.

**Balance**: Hierarchy is further supported by balance, which consists of three types: symmetrical, asymmetrical, and mosaic. Network visualizations often end up in a mosaic balance, where the data appears to be organized in a noisy demeanour lacking balance. Layout algorithms help reduce mosaic balance by attempting to provide organization to a network, but it sometimes difficult to completely balance a network visually. Some layouts, such as an orthogonal layout help improve balance by applying stricter rules on how edges should be drawn and how nodes should be placed. Visual balance should be considered in physicalizations, such that the overview of the network is legible. Ideally, a network’s physical properties should be balanced, such that it is not difficult to interpret the data through receptors.

**Colour**: The final design principle colour, is additionally affected through balance, and helps create hierarchy in a physicalization. Justin Stewart’s physicalization work “Regroup” [18] conveys hierarchy through colour in a large data sculpture to show ex-Google employees and the companies they formed after leaving. In the sculpture, Google is represented darker to contrast against branching companies, with bigger companies having more saturated colours. Additionally, the Regroup sculpture uses colour variety such that colours complement each other and do not contrast unless intended. Minimal use of colour is encouraged, since the representation will become too noisy if there is too much variation. However, a noisy approach to colour can work if that’s intentionally what the designer is trying to
communicate. Dorota Grabkowska’s installation “What Made Me” [7] intentionally becomes noisy to show the varying thought process of people as observers connect strings to different words in response to thought provoking questions.

In summary, we have addressed that before creating a physicalization and encoding physical characteristics, the design principles, as discussed above, need to be considered. Tools for generating physicalizations in contrast to hand-crafting physicalizations also need to have these design principles embedded into their design. In respect, the information that the physicalization is embodying needs to be communicated effectively through visual and physical means. Physicalizations that exist within the arts world provide good reference examples, as they were designed from the ground up for the physical world, as opposed to traditional visualization, which mostly derives from the digital world. In addition, most are aesthetically attention grabbing and use design principles effectively.

**Instantiation**

In order to make data physical with minimal effort, tools must be developed that can embody physical principles into an instantiation autonomously. We describe automation as a machine constructing the physical representation from a user’s input, such that they are not required to create it directly by hand. The input would pertain to the dataset, which may be subjected to filtering to emphasize specific points within a network. In addition, the input would consist of the design, with all encodings derived from identifying the design principles and the physical characteristics the user wishes to embed. The output, would create the physicalization through a machine, with the desired material or materials, for example, Polylactic acid (PLA), Acrylonitrile Butadiene Styrene (ABS), or Acrylic. Automation can be achieved by 3D-printing, laser cutting, or milling. However, in respect, current applications that can create or assist in the process of creating a physicalization are not aware of the design principles we discussed above. 3D-Printing applications merely print out a model with desired materials, and are not aware of the data within the instantiation. In that respect, the next ideal step is to create physicalization software equivalent to modern data visualization applications. For example, in modern visualization software such as Tableau [20], or frameworks such as D3 [3], unity is preserved by a virtualization’s immunity to disruption. For example, a layout algorithm of a virtual network can be re-executed if the unity of the layout is altered or broken through interaction. However, as we discussed in identification, gravity and people interacting with the physicalization can break physical unity.

Therefore, physicalization software should consider the space that the generated work will be placed in, and how much tensile strength is required, such that unity and organization is not significantly affected. Additionally, in regards to space, visualization software will apply rules based on the relationship between foreground and background elements. For example, visualization software may automatically decide upon a white font colour on foreground text upon a dark item in the background.
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to improve legibility. When considering colour and material for physicalization, the software should be aware of the background the physicalization will be placed in, in respect to figure-ground. In theory, the physicalization software should contrast the printed representation to the surrounding environment unless intended otherwise. In regards to space, physicalization software could consider the temperature, olfactory, and sound of the surrounding environment (see Figures 5, 6). In that respect, we can contrast or resemble a physical space’s properties, depending on how we want people to perceive the data we are conveying. Dominance, hierarchy, and balance can potentially be perceived through receptors based on evidence from Embodied Cognition [5, 17, 23]. Thus, there should be automated tools in place to allow designers to experiment with receptors to affect cognition and perception. Physicalization designers should be able to examine using texture, stiffness, temperature and weight the same way that modern visualization designers experiment with colour, shape and size through software. For example, designers should have access to automated schemes to affect physical perception the same way visualization designers have access to automated colour schemes (see Figure 10).

We have developed software using the Unity Engine as a step in this direction that allows users to input a network dataset which will produce a virtual 3D mesh representation that can be 3D-printed. The resulting network sits on a measured grid in millimetres to give the user a close indication of the size of the print (see Figure 8). After a force-directed algorithm runs on the layout, the software allows users to manipulate the network through a variety of tools. For example, re-positioning nodes with a mouse, applying edge bundling, switching from 2D to 3D layouts, and applying colouring. Over several iterations of creating physical networks (see Figure 7, 9) through the software, we have extracted potential features for instantiation of physicalizations discussed above. To fully leverage the design space of data physicalization, physical characteristics are a necessary addition to the potential of physicalization software moving forward. In summary, we outline the following features as possibilities:

- Awareness of the physical space’s colour, temperature, sound and olfactory (see Figures 6, 5).
- Inbuilt schemes to affect physical perception including texture, stiffness, temperature and weight that adapt to the data (see Figure 10).
- Modify tensile strength according to how the physicalization will be used. For example, whether the physical representation will remain stationary on a table or be tangibly interacted with.

**Evaluation**

To determine if the physicalization created is comprehensible by the intended audience, it is useful to empirically evaluate the instantiation. The type of audience the physicalization is intended for will usually affect the type of evaluation that will be performed. Such domains physicalizations appear in

Figure 9: Network physicalization consisting of replaceable nodes with flexible material.

Figure 10: Assigning a palette to temperature for instantiation.
include the art world, education, and immersive analytics. Despite the domain, all physicalizations should be assessed by how it affects the perception and the cognition of the information it is embodying. Approaches to evaluating physicalizations effectively remains an open problem, however designers could pertain to evaluating against a baseline condition, such as a traditional virtual representation of the data, or a pre-existing physicalization. Additionally, as stated by Jansen et al. [11], consistency has to remain across conditions for fair comparisons. For example, to avoid experimental bias, it is not fair to compare a large animated virtual network with an array of features in virtual reality to a static small physical network in reality. To completely understand physicalization, we need a fair comparison that allows us to single out and study aspects of physicalization in isolation. Likewise, physicalization creators should demonstrate how their interpretation differs from pre-existing representations to justify their reasoning for creating a physical representation. For evaluation, assessing a physicalization could pertain to measures such as memorability, engagement, accessibility, usability, comprehensibility, and perception.

CONCLUSION AND FUTURE DIRECTIONS
From this discussion, we have outlined three stages (identification, instantiation, and evaluation) applicable to the iterative development cycle of generating physicalizations. Additionally, we proposed a list of features that need to be developed within physicalization software in order to fully utilize the potential physicalizations have to alter perception of data. Likewise for future work, we plan to further prototype how to embed these principles into software. We would like to experiment with these properties to validate if physicalizations have significance in memorability and perception against traditional information visualizations. Furthermore, investigating significance in the area of network representation.

ACKNOWLEDGMENTS
This work has been supported by the Data to Decisions Cooperative Research Centre whose activities are funded by the Australian Commonwealth Government’s Cooperative Research Centres Programme. We also wish to thank the Australian Research Council and the University of South Australia for partially funding this project. Additionally, this work was supported by the Australian Research Centre of Immersive Virtual Environments.

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