The Role of 3D Printed Objects Facilitating the Process of Mutual Communication and Collective Idea Generation Between Scientists and Designers

By

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ABSTRACT

The arrival of 3D printing technology, otherwise known as additive manufacture, has had a profound influence on the design and manufacturing fields. It has significantly reduced the cost of design and increased its accessibility to diverse industries, such as science and medicine. Despite the remarkable technological improvements in 3D printing technology, there are still diverse challenges that scientific laboratories encounter when using such equipment to develop customized lab equipment. A major challenge is successfully transferring and incorporating the scientists' ideas during the design process using the 3D printer due to their limited experience in design practices.

The majority of the literature on 3D printers and the design field focus on its manufacture benefits. This paper fills a gap in the existing literature and explores the role of 3D printers in the ideation process of design, specifically in the context of Co-design environments with scientists. It is argued that 3D printed objects can support ideation by allowing enhanced engagement between participants, helping uncover important insights and increasing the team's idea generation process, as well as enhancing the clarity of communicating these design ideas.

A workshop was conducted to test this hypothesis at the University of Ottawa Laboratory of Cellular and Molecular Medicine with neurobiologists and engineers. The results of the workshop demonstrated that the 3D printer could support scientists in the ideation process by enabling different domain-specific types of interactions. In the case of the scientists, realistic simulations brought by 3D printed objects displayed an opportunity to explore a design

challenge through different perspectives and domain knowledge lenses. In addition, two examples of collaboration with the group scientist using the 3D printer and co-design practices will be presented.

ACKNOWLEDGEMENTS

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GLOSSARY

IDEATION – The third stage of Design Thinking. Refers to the early design process and the stage where ideas are generated. It involves the creative process of generating, developing, and communicating new ideas.

IDEA CREATION – The action of engaging in cognitive idea generation.

SCIENTIST – Refers to non-designer participants with a professional background in science (e.g., Neurobiology).

RESEARCHER – The design researcher and author of this thesis.

DESIGNER – A professionally trained designer.

DESIGN THINKING – The human-centered, cognitive, strategic and practical processes of how designers think, developed by designers to develop design concepts

1. CHAPTER I – INTRODUCTION

Existing literature on design thinking demonstrates that there are differences in the ways that designers and scientists develop creative thoughts and approach design problems. In particular, and although not a strict rule, scientists tend to approach problem-solving from a systematic and analytical lens (Lawson, 1980), while designers tend to focus on multi-linear or lateral approaches to solve problems. As a result, when scientists are confronted by a challenge requiring creative solutions, they tend to struggle with abandoning linear thinking and a systematic approach. This affects the range of creative solutions that they can generate and communicate with one another on their own.

In the field of design, increasing attention has been given to participatory design processes, particularly to Co-design (Steen, Manschot & De Koning, 2011; Sanders & Stappers, 2008). Co-design, also known as generative design, participatory design or cooperative design, has its roots in the design techniques developed in the '70s by Scandinavian designers. (Sanders and Stappers, 2008). The concept refers to the process of involving the stakeholders who benefit from the design into the design process. It is a combination of generative and exploratory research in order to define a design challenge, with a developmental design approach. Co-design researchers refer to this concept as an act of collective creativity, which translates into the act of creativity being shared by two or more people. In this sense, the term Co-design refers to the application of collective creativity throughout the entire cycle of the design process.

At the heart of Co-design, the ideation phase is the space where idea generation is concentrated and where source material and insights are born and shared in order to achieve innovative solutions for the end-users. It has become a popular approach to design because it helps bridge design-specific knowledge with domain-specific knowledge from non-designers in order to generate further ideas. In the context of the science field, Co-design could help unleash creativity and deviate from common linear ways of thinking.

To enhance Co-design practices, designers have developed tools and approaches to provide people with different ways to engage with each other throughout the ideation phase to enhance creativity and uncover hidden insights relevant for solving the design challenge in a project. These tools, techniques and approaches support diverse levels of participation throughout the entire design process and with different stakeholders, allowing participants to design alongside the designer. For example, simple group brainstorming, sketching and prototyping techniques are used to increase the engagement of participants by enabling immersion, empathy and dialogue which are used by the designer to understand the distinctive points of view of the rest of the participants and end-users (Müller, R. M., & Thoring, K. 2012). This study explores the use of 3D printing as one of these tools to generate tangible objects to help engage participants in the design process, inviting novice and expert participants, both designers and scientists, to develop their creativity through an empirical funnel.

The arrival of 3D printing technology has had a profound influence on the design and manufacturing fields. In the past few decades, 3D printer machines have reduced the cost of design significantly, thus increasing its accessibility to diverse industries such as automotive, aerospace, fashion, science and medicine. The current literature on 3D printing in design mostly focuses on the benefits it has for manufacturing. The creative advantages of the technology for Co-design have been largely unexplored, specifically, the benefits for idea generation early in the design process.

Currently, some small laboratories are already investing their resources in low-cost 3D printers in order to develop scientific equipment such as simple labware, medical representations and prosthetics. Despite the remarkable technological improvements in 3D printing technology, there are still some challenges small laboratories encounter when using such equipment. One of such challenges is to successfully translate their creative ideas into the actual design in order to design their lab equipment. Instead, scientists often rely on improvising with third-party products, which limits its use to the specific intended purpose of the item, or outsourcing design, increasing overall costs and taking the design process away from the end-user. In general, low-cost 3D printers in science-related fields have brought benefits such as avoiding high costs of getting products from big intermediary companies and being able to tailor products to their own need in shorter times.

The benefits of 3D printing are becoming more accessible to anyone who can get their hands on this technology, however, harnessing its full potential requires certain skills and knowledge. Due to the average scientists' lack of extended knowledge in design practices, 3D printing, and 3D modeling technology, they often have difficulty in developing the creative process to design such tools on their own and end up relying on the open source community and the outsourcing of design work. In addition, acquiring the necessary skills represent a learning curve that is simply too steep. Work-related time constraints and lack of design interest can also prevent them from adequately following a design process, therefore, missing opportunities to accurately communicate their creative solutions. Many industrial designers have the specific skills to use 3D printers, such as knowledge of design methods, digital tools for 3D modeling, graphic design and facilitation qualities that allow them to be able to communicate ideas through visual means (Yang, You, & Chen, 2005).

There is limited knowledge on the role of the 3D printer in aiding the non-designers ability to communicate and generate ideas in a Co-design environment. This raises the research question of this study: *How can 3D printers facilitate the process of mutual communication and collective idea generation between scientists and designers in order to aid in the generation of new or refined ideas and uncover hidden needs to further the design process?* In this paper, it is argued that the low-end cost spectrum of 3D printers can enhance the collective ideation process of scientists by enabling creative play and simulation with physical representations of their initial ideas.

This argument will be explored through several sections. The first section will provide an overview of the 3D printer and its current benefits and influence on various industries, in particular, the science fields. This will be followed by a review of available literature on the different mindsets designers and non-oo use when applying problem-solving strategies. The practice of design thinking and Co-design will be described and applied to the context of small budget laboratories. The second section of the paper will present a case study used to explore the hypothesis through a small workshop conducted by the author at the University of Ottawa Hospital with scientists. The workshop introduced the 3D printer as a tool for ideation during Co-design sessions to design and fabricate a prototype for a piece of laboratory equipment, followed by some more in-depth examples of the workshop approach in practice. The thesis will conclude with a discussion of the findings of the case study, two examples of this type of collaboration with scientists and future research opportunities.

2. CHAPTER II - LITERATURE REVIEW

2.1 3D PRINTING

2.1.1 HISTORY

Understanding the history and evolution of the 3D printer is important for later understanding its role in the context of design. In the 1980s, Charles Hull invented the first 3D printer, called “stereo lithography,” which allowed digitally fabricated models to be interpreted from a digital file through Computer Aided Design (CAD) tools and then turned into printed objects using photopolymers (Gross BC 2014). The novel invention allowed designers to communicate shape, color, texture, and thickness from a digitally created design into a physical printed object.

Almost a decade later, the first commercially available 3D printing system (SLA-250) was introduced. Additive manufacture, otherwise known as “3D printing”, is the process of joining material layer by layer to generate an object from 3D modeled data rather than subtracting from any type of material (Lipson and Kurman, 2013). The application of 3D printers, initially known as “rapid prototyping machines” (Bradshaw et al., 2010) has been steadily growing amongst various industries. The term, “rapid” referred to its capabilities to fabricate something in a short period of time, in contrast to the process of manufacture using conventional machining. Also, the word “prototyping” refers to a cost-effective way to do further refinement and to make a tangible object before it goes to mass production (Bradshaw et al., 2010).

Since then, many companies have developed their own version of the 3D printing machine which has had an impact not only on the manufacturing industry but also the market of personalization and mass customization in small and medium-size companies. Recently the application of 3D printer technology has been broadly expanded to fields such as the aerospace, fashion, medical, and healthcare fields. (Bullis, 2011).

The rapid development of 3D printer technology has resulted in the decreasing cost of 3D printers during the past decades. While advance professional 3D printers remain very specialized and costly machines that can cost upwards of several hundred thousand dollars, small low-end consumer 3D printers can range in price from $150 to $2,000 USD. Low-end consumer 3D printers can produce objects in a limited selection of materials but the development of compatible materials is continually developing by technologists, engineers, hobbyists, and environmentalists. In general, the output quality from these low-end consumer printers cannot reach consumer market standards. Nonetheless, the technology has been welcomed by designers, hobbyists, and creators alike as a great tool to tackle the diverse challenges of product development in different sectors and industries.

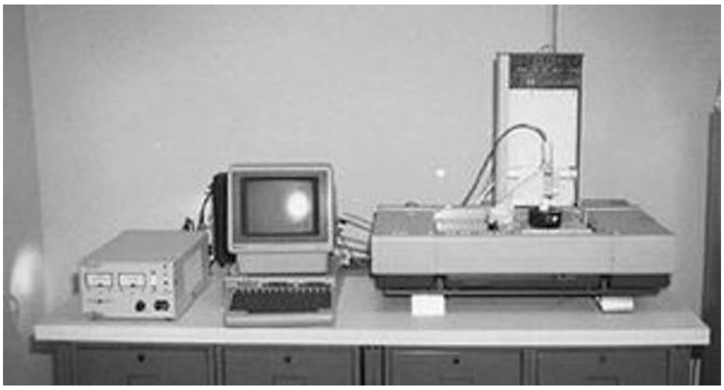

Figure I. 3D Systems (1988, Dec 5) Model SLA-250, first 3D printer version released to the general public for commercial use.

2.1.2 BENEFITS OF 3D PRINTING IN THE INDUSTRY

There are several critical factors that make 3D printing a promising technology for industries where design is required. For one, it allows designers to develop low volume, low-cost productions which provide market advantages such as mass-customization and rapid-prototyping. Additionally, it shifts the scale of production from a large and corporate scale to a small and domestic scale. This enables self-manufacturing capability which provides a huge benefit for the individual designer, as well as small design firms who wish to develop products without going through the traditional manufacturing procedures (Richardson & Haylock, 2012; Troxler, 2011). These benefits of 3D printing revolve around increasing the products' value by enhancing the efficiency and effectiveness of the design process and can be categorized into four main areas:

- Enhanced functionality
- Reduction of costs and time
- Enabled iteration practices
- Education

2.1.2.1 ENHANCED FUNCTIONALITY

It is typical in product development to undergo ergonomic and functional analysis. 3D printing enables initial testing and experimentation early in the design process. For example, 3D printing is being used to produce ceramic molds with surface textures that can change the functional aspects of a product, transferring specific functionalities to a given surface such as gripping, or even temperature transfer (Alain C. Emanueal S, Salvatore C.

2000). The capacity of controlling aspects such as the value of layer manufacture during the process can have other beneficial effects on the design process, resulting in the minimization of flexibility costs, capital cost, and marginal productions. (Koren, 2006; Dolgui and Proth, 2010; Berman, 2012).

When control of functional aspects of the design is conveyed in the early stages of the design process, it allows for initial quick testing, failing and fitting of ideas. For designers, engineers, architects, educators, and creators in general, it can take several weeks or months to create concepts which are able to provide the right direction for a product. 3D printing can help by creating multiple iterations of functional prototypes in a day or two and even in a couple of hours. Additionally, it allows the designers to have better control of the design by performing functional and usability tests early in the design process and in the overall product development process.

An example of the benefit of enhanced functionality brought by the 3D printer in the field of science is an article published in the Physical Review by a team of mechanical engineers at Boston University. The article describes how the engineers developed a 3D printed object with a complex metamaterial that could allow air-flow, but restrict sound emission, solving a wide range of problems in the car and aero spatial industry (Reza et al. 2019).

2.1.2.2 REDUCTION OF COSTS & TIME

One of the most well-known advantages of 3D printing is related to direct and in-direct cost-savings for industries. For most businesses, costs of manufacture are crucial to their operation and 3D printing can directly help to keep expenses low by saving resources from three categories: machine operation cost, labor cost, and material cost. In addition, by reducing the time of production and design, the product is able to get to the market faster which ultimately saves money.

With 3D printing, machine operation expenses represent a small part in the overall cost of the fabrication process. Using traditional manufacture in an industry environment to generate complex objects requires high levels of energy and resources. In contrast, creating complex shapes and products in a single step through 3D printing requires significantly less energy and human-resources. 3D printing technology offers increased efficiency which benefits the design and manufacturing process. The overall control over the production and design process brought by the 3D printer makes it possible to fine-tune the design and fabrication details in order to ensure the highest productivity level. Machine operating cost in traditional manufacture is simply offset by the capabilities of using the 3D printer during the manufacturing and design process.

For example, Exalto, a company which designs, produces and supplies quality wiper systems for leisure, commercial and rail markets, used 3D printers to speed up their design development process by keeping the prototyping stage in-house, shortening the intermediate steps in the process of design to finally reduce costs by 60% (Tractus 3D, n.d). The company was able to plan efficiently, test and verify various design iterations in a short period of time before ensuring that the final product was ready for production.

3D printing also keeps labor costs low. While in traditional manufacture there are numerous people required to operate a number of machines or production lines, only a single operator is required to start the 3D printing machine before it begins its automated pre-configured process of fabricating. Consequently, labor costs are lowered as there is no real need for specialized machinists to operate tools of manufacture during the process.

Finally, 3D printing can use an increasingly growing range of different materials. This allows iterations and changes to be done during the mid-design process by simply swapping a cartridge or material spool. This maintains the overall cost of design development and production and keeps it lower than with traditional methods. The diversity of materials available makes the 3D printer adaptable to every industry, and there are continuous efforts to expand the quality and quantity of the available materials additive manufacturer can use (Mertz L. 2013).

2.1.2.3 ENABLED ITERATION PRACTICES

3D printing and CAD technology allow designers and manufacturers to rapidly fix or reconstruct design structures. This gives the ability to create more variants faster while spending less money on the manufacture of each piece or parts of a product (Mertz L. 2013). The speed in which 3D printers can create allows designers to waste less time by generating continuous design. This is a reality that would simply be impossible to achieve with traditional ways of manufacture.

The prosthetic industry is an example of an industry already taking advantage of this benefit. For Orto+ laboratory, a prosthetics company, the process of using 3D printing technology has revolutionized the way they work. It has allowed them to create multiple iterations of their prosthetics at the same time, ensuring consistency and reliability of all designs, while maintaining customized fit for every client. Orto+ noted that it now takes generally two or three design iterations before the final design is completed when using 3D printers. In general, 3D printing technology has allowed them to create individualized designs in a shorter period of time, which resulted in cost-efficiencies and reduced labor (Tractus3D. n.d). In this case, 3D printing was used to iterate versions of a product rather than for iterating on ideas.

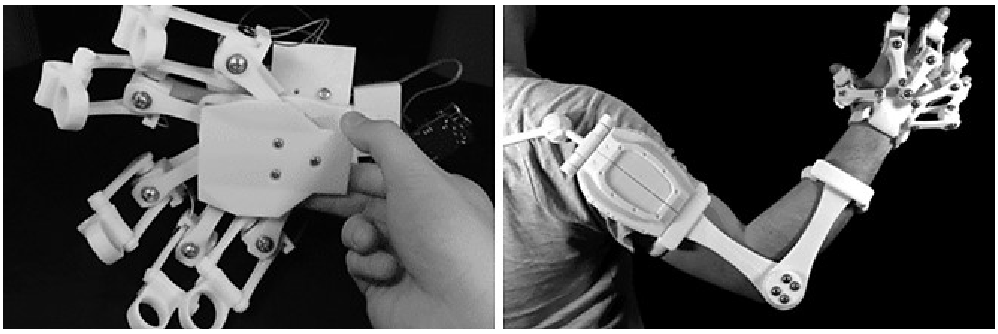

Figure II. (left) 3D hand prosthetic variant. (right) final 3D printed orthopedic prosthetic. Tractus3d (N/A). Retrieved from https://tractus3d.com/3d-printed-prosthetics-reduce-labor-time-immensely. (2018)

2.1.2.4 EDUCATION

There is more than meets the eye when it comes to an understanding the benefits of 3D printers. An example of a less discussed benefit surrounding the impact of the 3D printer is education. For educators and academics, the 3D printer has shown real advantages for learning and teaching and has created a lot of flexibility in the classroom. Educators can let students actively engage with whatever subject they are learning in class via physical prototypes. Fully functional models of gear systems for engineering or representative examples of the human body for medics are some examples of how this technology can help teach students more effectively. The core concept is that realistic representations of objects can effectively be used to teach more efficiently by allowing the students to have a better understanding of the concept, enabling physical interaction and allowing processing of cognitive thoughts through physical assets, improving the way of absorbing and uncovering information.

Such is the case of “Güggeltown”- a project led by Kurt Meister at the School of Steffisburg and Gregor Lütolf at the University of Teacher Education Bern (PHBern). In this project, students were introduced to a 3D printing workflow to create their own version of a city (Gregor L. 2013). This exercise aimed to inspire curiosity and promote a deeper understanding of urban necessities through the potential of 3D printing technology, a benefit aligned to the creative aspect of this tool and how it can benefit outside the scope of manufacture.

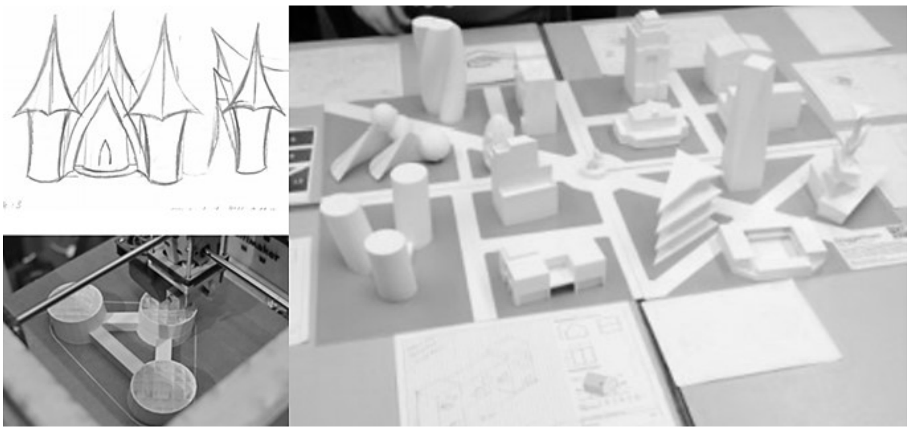

Figure III. (left-top) Initial student input (left-bottom) 3D printing initial ideas (right) Güggeltown final project. Reproduced from Lütolf, G. (2013). “Using 3D Printers at School: the Experience of 3drucken.ch. Low-cost 3D Printing for Science, Education and Sustainable Development”, ICTP—The Abdus Salam International Centre for Theoretical Physics, Triest, 149-158.

2.2 3D PRINTING IN MEDICINE AND SCIENCE

2.2.1 3D PRINTING FOR MEDICAL RESEARCH

In the medical, healthcare and science fields, 3D printing is being used to generate a wide range of solutions, from printing surgical implants to enabling collaboration and sharing of laboratory equipment (Jones, D. B.; Sung, R.; Weinberg, C.; et al. 2015). In particular, 3D printing technology has had a significant impact on the medical industry and changed the way patients' conditions are treated. (Mertz L. 2013). The number of medical products and services relying on 3D printing technology have continued to grow and have been applied to a wide range of applications such as prosthetic design, including printing ear, bones (Gross BC. 2014), eye corneas (Hoy MB 2013), dental and body prosthetics (Cui X. 2012), windpipe supports (Lipson H. 2013), bandages and casts (Ursan I. 2013) and laboratory equipment to support scientific developments (Coakley and Hurt, 2015).

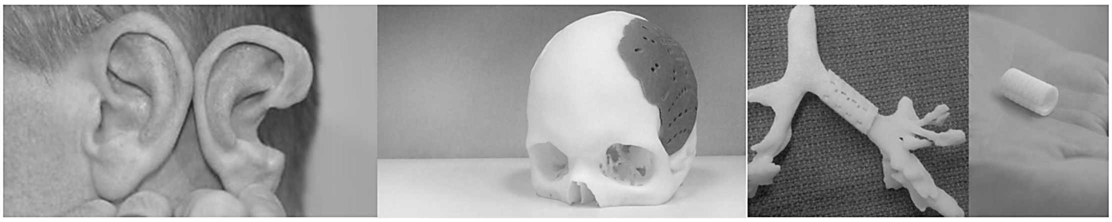

Figure IV. (Left) 3D Spectra Technologies. 3D printed ear prosthetic (2017, Aug 29). (Middle) OsteoFab 3D printed bone prosthetic (2013, Mar 7). (Right) Materialie ©. Replica of trachea/bronchus using scans and 3D printed splint that would support patients' airways

Undoubtedly, one of the most significant advantages brought to the science and healthcare industries by the 3D printer is the freedom of being able to create one-of-a-kind custom-made medical tools and equipment. (Banks J. 2013). For example, 3D printing is now being used by physicians to create customized fixtures and implants for patients in the operating room (Banks J. 2013).

Hearing aids and teeth brace products are another example of 3D printed products assisting the science fields made from digitally scanning a patient's mouth or ears (see Fig V). Almost all hearing aid apparatuses are custom made to fit the different size and unique form of the user’s ear and patient’s mouth (Lipson H. 2013). 3D printing enables this flexibility for anyone to get user-fitted products to benefit their health.

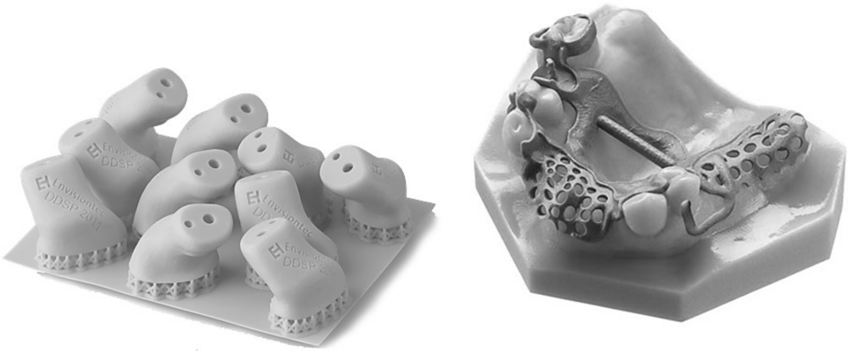

Figure V. (Left) EnvisonTec © (N/A) Patient custom made hearing aids printed with resin 3D printers (Right) Stratasys © (N/A) 3D printed tooth brace custom design for patient

Furthermore, Francis Collins, Director of the National Institutes of Health (NIH), stressed that 3D printing technology has become “a potential game changer for medical research” (NIH launches 3D print exchange for researchers, students. 2014). This is why NIH has established a 3D model exchange portal (3dprint.nih.gov) to support free online open-source files that can be shared (see Fig VI). Some examples of these 3D printable resources are custom labware, anatomical models, and so on. (Coakley MF, 2014). Additionally, researchers can access 3D model files available in open-source repositories such as Thingiverse, Pin shape, and MyMiniFactory platforms created to allow any user to access 3D files for low or no cost. These platforms also allow sharing of design ideas and skills between designers and scientists, opening a door of opportunity for collaboration (online or physical).

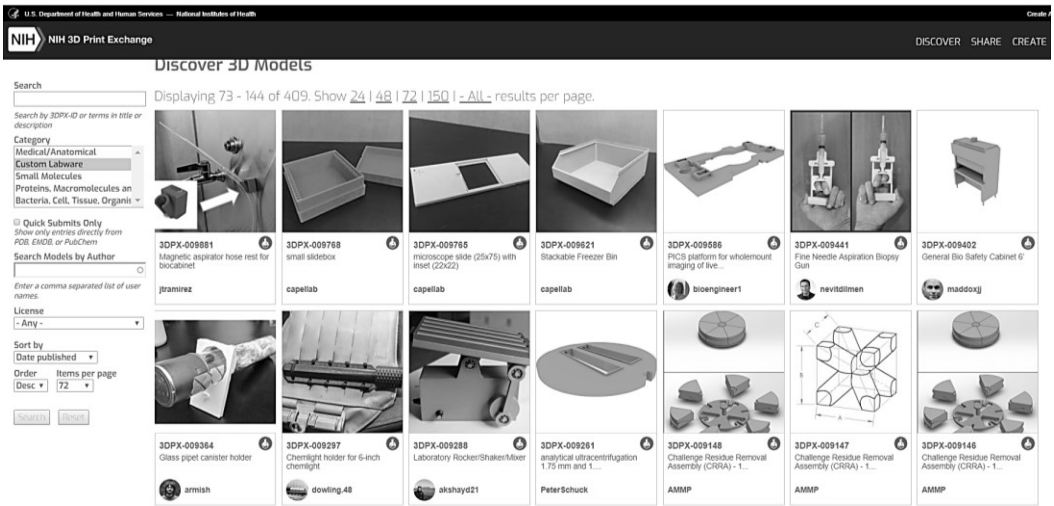

Figure VI. U.S. Department of Health and Human Services, NIH. (Accessed 2018. Dec 10). NIH 3D print exchange portal showing some labware available for download and print.

Even though the applications of the 3D printing in the medical industry is rapidly expanding, the overall impact that the technology has had is still relatively minor compared to other industries. This is because most of the applications mentioned previously require high-end, expensive 3D printing, which laboratories with a small budget cannot access. However, this has not stopped small laboratories from benefiting from the technology. Instead of relying on costly specialized 3D printing machines, some low-budget science research laboratories have adopted the low-cost range of 3D printers to assist them in their science and design challenges.

2.2.2 3D PRINTING IN SMALL SCIENCE LABS

For small scientific laboratories, the primary interest in 3D printing comes from the possible cost-benefit of being able to produce customized lab equipment that fits their own research needs. There are several examples of academic and corporate cases where thousands of dollars have been reported in savings by using the 3D printer as the preferred method to design scientific equipment and tools. For instance, the Public Library of Science released an article on how a scientific piece of equipment was designed using low-cost 3D printers which resulted in a 97% cost savings for development. (Zhang, Anzalone, et al. 2013)

Typically, the development of a customized tool requires significant time for planning and fabricating which small labs do not have. Instead, this process is often outsourced to expensive medical product development companies which require a significant financial investment. For example, the cost of a typical syringe pump can range from $250 to $2,500 USD from a specialized medical equipment manufacturer.

The issue of keeping costs down while increasing productivity has been a challenge for small scientific laboratories given their limited research budgets. To overcome this challenge, scientists have employed low-end 3D printers to create multiple prototypes and maintain the convenience of altering or changing their design ideas until they have entirely satisfied a solution. Joshua Pearce, a professor in the Department of Materials Science at Michigan Technological University, managed to Co-design a 3D printed syringe with his engineering class that cost barely $50 USD and was able to perform the same function of the expensive commercial syringe pump. (Wijnen B. et al. 2014).

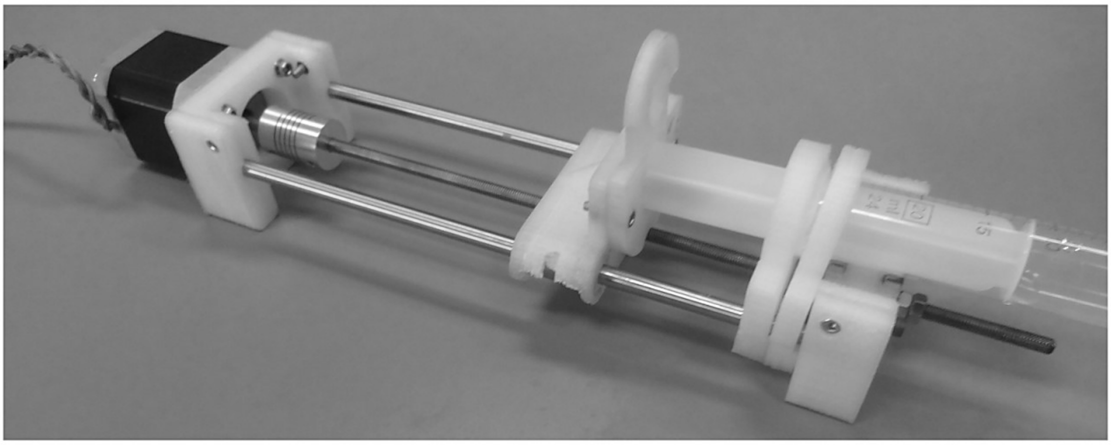

Figure VII. Joshua Pearce (2014). Open-Source 3D printed Syringe Pump Library. PLoS ONE 9(9): e107216.

Another example of how this technology is being adapted into small scale, low-budget science research laboratories is the case of Troy Hibbard at the Trinity College of Dublin. He and other scientific researchers used a low-cost 3D printer to design their scientific devices inside the scientific laboratory. Hibbard went from improvising with everyday household items such as paper clips, duct tape and coffee filters to fully customizing and 3D printing scientific lab equipment with similar physical characteristics to any other third party commercially available product. In his lab, the 3D printer has become a core player in the development of the design for science, aiding in the prototyping and product development of lab equipment such as Homogenizer tube holders, tubing mounts for laboratories faucets, and tube racks (Coakley and Hurt, 2016).

Similarly, Burgess Harold, a senior investigator at NIH, discussed how scientists use 3D printing technology in a timely and cost-effective way by collaborating to design components to fit their research purposes and house their research live specimens safely (Coakley, M., & Hurt, D. E. 2016). Burgess used the technology to create a series of prototypes that would have otherwise cost thousands of dollars (See Figure VIII). With the technology, his team was able to quickly ideate, test and validate the prototypes of a plug that would prevent fish from escaping into areas where they were not supposed to be. Burgess points out how this design and manufacture tool has helped their research financially as well as saved them time. He stresses that the 3D printer helped him to go through multiple design iterations within a short period of time with lower costs than ever (H. Burgess, 2015). He then goes on to explain how this iterative process would have traditionally cost several thousands of dollars by using machine workshops, and the design cycle would have taken two weeks per iteration (Coakley and Hurt, 2016).

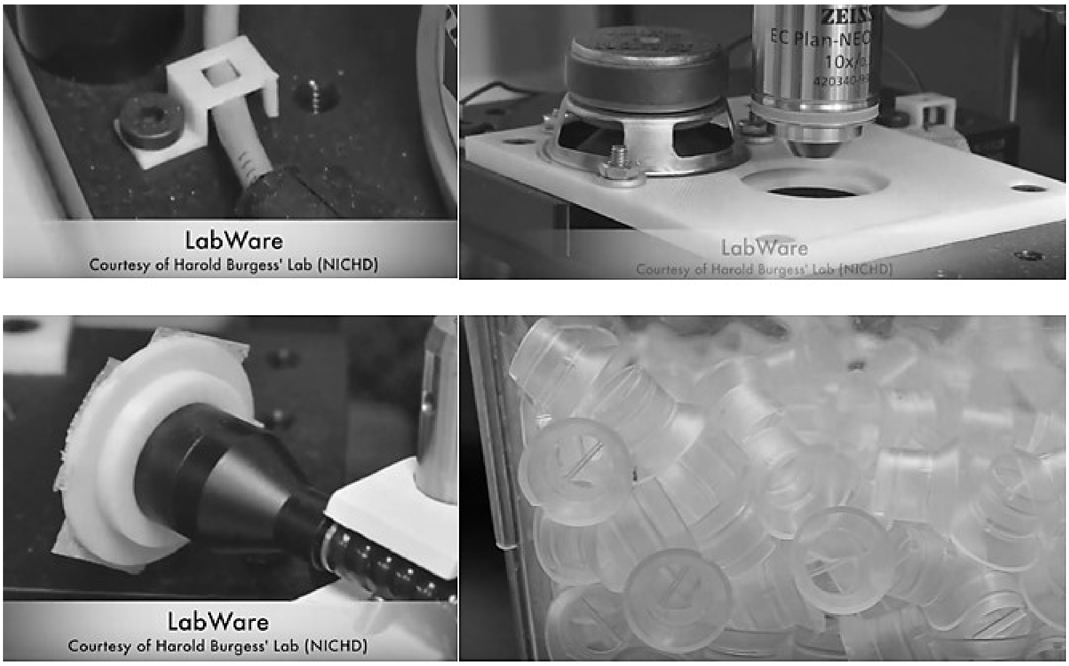

Figure VIII. 3D printed labware from Harlod Burguess' lab. (NICHD). Image credits: Screenshots from "Examples of 3D Prints at NICHD," NIH 3D Print Exchange YouTube Channel, video by Jeremy Swan published on January 31, 2014

Burgess acknowledged that the 3D printer could help people to unleash their creativity (H. Burgess, 2015). However, in his work, he only used the 3D printer for trial and error design rather than to spark or enhance creativity and ideas.

These are examples of how collaboration through 3D printing can push scientific discovery and help to perform reproducible experiments for scientists, aiding in creating accurate scientific data to support their hypothesis, which is the maximum benefit for science.

2.2.3 CHALLENGES FOR THE SCIENTIST IN USING 3D PRINTING FOR DESIGN

Even though 3D printing has already provided several benefits for scientists, there are still challenges for them to adapt the technology to their lab environment fully. It is important to note that designing a product requires skills to operate tools such as 3D printing as well as domain expert knowledge in design. Richard Buchanan (1992), professor of design and innovation, argues that most people continue to think of this technology in terms of its product rather than as a discipline of systematic thinking (Buchanan, R. 1992). While it is possible to operate one of these machines with little to no experience in design, to un-tap the true design potential for creative development, and not only the manufacturability aspect, 3D modeling or CAD software must be applied to be able to generate a design. In addition, in order to create valuable products, an Industrial Design process should take place. Since scientists are not trained in design, they may have a hard time developing proper design processes of their own lab artifacts for their research even if they have access to a 3D printer. For example, Dr. Darren Boehning, a professor at the University of Texas Health Science Center at Houston initially brought a 3D printer into his lab and realized that it required experience and knowledge in order to operate the machines and make his own design (Boehning, 2015). This challenge can easily be overcome by investing time in learning the mechanics of 3D printing and is considered a minor challenge.

The real challenge scientists may encounter when designing for their lab comes when they are required to design, customize or personalize their equipment for their specific needs. This process usually requires a thorough thinking and ideation process and, because scientists are not trained as designers, they often struggle with coming up with the proper design workflow despite having access to a 3D printer. To address this challenge, some laboratories rely on hiring third-party design firms or designers which may leave the scientist outside the design process due to the client-designer relationship. When laboratories approach their design challenges by hiring outside design firms, they do not usually have an active role in the design process and their hidden insights might remain unexplored. For small laboratories looking to explore novel and sometimes unique research through new lab equipment, such as the one featured in the workshop discussed later, the approach of hiring outside designers can be an inefficient process and it often requires high levels of investment in terms of time and money. Other laboratories simply rely on online repositories such as the one offered by NIH (see Fig VI), which limits their choices of design to the designs available online. Although it is possible for laboratories to upload and download 3D printable ready files, some labs require specific and customized designs that are not commonly used and thus not available online.

Another challenge for small laboratories is how to properly iterate new ideas to solve a specific design challenge in contrast to iterating from a product or specific design. By not being able to properly apply a design process, initial ideas are potentially taken as final solutions thus limiting the scope of solutions being explored to address the design challenge.

To address these challenges, design thinking and Co-design can offer interdisciplinary collaboration that includes the scientists as active participants in the design process. Understanding how designers think and the diverse mindsets of participants (especially non-designers) in Co-design is important to understand how this type of collaboration can be especially helpful to address the scientists' challenges and enhance their creative thinking and iteration practice when it comes to design.

2.3 DIVERSE MINDSETS

To understand the real impact of how designers think and the benefit of having designers working around multidisciplinary teams, it is important to understand how it is that designers come to solve problems individually by using a proper mindset and in groups by using creative methodologies to access the participants' insights. Donald A. Schon agrees that designers apply their innate artistic ability to solve non-quantifiable problems that cannot be addressed through analysis or any scientific logical mean (Schon 1988). Nigel Cross and Roger Martin, amongst other researchers, identified similar kinds of reasoning as crucial for thinking like a designer. They call this type of reasoning, “abductive reasoning”.

From the mindset reasoning studied by design researchers, abductive thinking seems to be the closest way to describe how designers think. Contrary to the known counterparts (induction and deduction), abduction is usually regarded as the “logic of what might be” (Martin R. 2013). This embodies the context of how designers think. Abduction can be regarded as a type of argumentation that fits the best explanation. It is a hypothesis which makes more sense grounded in observation and information gathered before actual experimentation. Abduction follows a logical process of considering the best guess to take the next step. This mindset allows for the generation of new information or knowledge and, unlike deductive reasoning, the result from abductive argumentation might show that the conclusion is false even if the premises are true or vice-versa (Thagard, Paul, and C. Shelley, 1997). Abductive reasoning follows very closely the concept of imagining, making it a more common mindset for creative people such as designers.

For designers, abductive thinking has been shown to be a particularly effective method to approach design problems and it is usually followed by design synthesis (Coyne 1988). Framing a design problem results in setting logical boundaries, allowing designers or non-designers to reach into their personal experiences with the hopes of bridging a logical gap based on groups of inconclusive and incomplete ideas (much as Douglas and Isherwood and N. Cross theory). An example of abductive thinking would be: A neurobiology scientist observes the test tube filled with mutated fruit-fly and sees the specimens turn red. He abduces that either there is oxide in the sample or his colleagues are playing yet another prank on him.

Deductive reasoning is the type of logic in which mathematics is based. A deductive argument will always be self-contained, meaning that any argument made with this mindset will not offer any surprise findings as it all follows a logical pattern. A deductive argumentation is one that guarantees the truth of the conclusion by a logical pattern (Kolko, J. 2010). In addition, deductive reasoning can be considered more closely related to the concept of reasoning rather than imagining, a characteristic that is also true for inductive reasoning. Deductive reasoning is a common mindset amongst scientists although they are not limited to it by any means, it and allows them to approach a problem from a linear perspective. An example of deductive reasoning would be: A neurobiology hospital identifies a trend that shows research grants to favor fruit–fly research. Scientists department deduces it can boost successful grant proposals by increasing the mention of the word "fruit-fly" for their next publications.

Inductive reasoning offers argumentation for evidence that something might be true based on previous experience. Scientific fields usually use this mindset to test their hypothesis. It is the assumption that every time you input something under a specific condition, it will have a specific output. Consequently, every other time you input, it will result in the same output. Repeating this experiment multiple times might eventually result in something else. Thus an inductive argument is one that does not guarantee the truth of the thinkers' conclusion. Induction, like deduction, does not usually result in novel findings because the potential logic of the argument is contained within the known argumentation. An example of this type of reasoning would be A scientist leaves for work at 8:00 a.m. The scientist is very punctual; Therefore the scientist assumes that leaving work at 8:00 a.m. will result in getting to work on time.

Taking advantage of the different mindsets, problem solvers such as designers can interact with different types of users (such scientists) and tap into more structured methods of accessing, gathering and generating information locked in the participants' insights. The merging of different mindsets helps enhance the ideation experience in the design process, as it allows the problem-solver to approach problems based on how the context in which they are framed. Design thinking encapsulates how designers think and approach design through the use of these different mindset reasoning, specially abductive thinking, which closely relates to the concept of imagining what might be.

2.4 DESIGN THINKING: IMAGINING AND REASONING

Design Thinking has become popular and gained momentum due to the rapid growth and evolution of modern technology and the modern business sector which required new and creative approaches to tackle design challenges (Jon Kolko, 2015). For designers, Design Thinking is regarded as a novel design literacy which facilitates a deeper understanding of how designers think and engage in the practice of design.

Throughout the history of design, several researchers have turned their attention to identifying design as a separate discipline from the arts and sciences. For example, design researcher Nigel Cross (1982) distinguishes the design knowledge as different from the types of knowledge from the disciplines of art and sciences. In his research, Cross strongly correlates design knowledge with a specific nature of Design Thinking taken from the research of Mary Douglas and Baron Isherwood (Douglas and Isherwood, 1979). In their research, Douglas and Isherwood recognize how human reasoning has for too long been constricted to deductive and inductive ways of thinking which in fact has limited the understanding of how different disciplines apply problem-solving strategies. They advocate for a type of reasoning that they describe as playing the role of “matching, classifying and comparing,” hinting at the power of “metaphoric appreciation” and the outcomes of finding patterns in unlike elements (Douglas and Isherwood, 1979). This is an important notion in Design Thinking because it demonstrates that design has a distinct way of thinking.

Bryan Lawson a professor of Architecture at the University of Sheffield, and author of the book “How Designers Think” argues that design and the way designers think can be considered as a separate discipline from the arts and sciences. In his theory of Design Thinking, he analyses significant differences between the thinking process of architects (related to imagining and creativity) and engineers (related to reasoning and analysis) (B. Lawson, 1979). In this case, “reasoning” is considered as a calculated, linear approach to moving towards a particular conclusion. In contrast, “imagining” refers to the approach an individual would take when drawing from personal experiences, combining the information in an apparently unstructured way. Also, Lawson does not rule out the use of imagining and reasoning simultaneously, instead, he refers to the balancing of these two as the most important skill of a designer (B. Lawson, 1979). Lawson’s definition of imagining is understood similarly to the concept of abductive reasoning, where thoughts are guided by recognizing patterns which are outside the scope of the designer’s base knowledge in order to compile new information which appears to be disorganized and not aimed in any particular way (B. Lawson, 1979). Similarly, Donald Schon describes Design Thinking as a way of making progress in which designers must make sense of uncertain situations which initially might make no sense (D. Schon, 1988). This type of reasoning is differentiated from the usual or “traditional” reasoning processes where the solution is already obvious and the designers only have to choose the most appropriate method to get a solution.

The distinction between these two types of reasoning lies in the idea that designers do not always follow the most obvious path solution. Instead, they explore the problem and the possible solutions from different and sometimes abstract perspectives. For example, Cross argues the design process is not a directly straight forward linear process; instead, the approach relies on multiple iterative processes and the reciprocity of information between possible solutions and the problem.

A number of researchers have explored the different problem-solving strategies adopted by designers and scientists. Although this is not a rule of thumb, these behavioral studies of design tend to support the idea that designers problem-solving strategy differs from that of scientists (Lawsons, 1979, 1980. C. Nigel, 2007). Scientists problem-solving approach tends to be described as systematic and analytical (Lawson, 1980), while the designers' approach tends to focus on multi-linear or lateral approaches based on synthesis. The main difference noted between these two approaches is that while scientists tend to concentrate their efforts on discovering that single perfect solution, designers constantly seek and encourage themselves to find a set of different solutions enabled by creativity. Designers usually adopt solution-focused strategies while scientists feel more comfortable following a problem-focused strategy (C.Nigel, 2007).

The biggest difference between these two problem-solving approaches is that designers tend to understand and learn about a problem as a result of testing diverse alternatives, while the scientists will tend to delineate a problem to extract specific information. Through Design Thinking, a designer seeks to understand the user with empathic and observational approaches. Interacting with the user throughout the design process helps the designer imagine the problem from different perspectives. Being aware of these different perspectives can help in defining the overall challenge and prevent it from being overlooked with conventional observation techniques (Brown, 2008). The Design Thinking process is usually composed of five or six distinct steps: definition of the problem, observation, ideation, prototyping and implementation (Nussbaum, 2004). These steps do not necessarily follow a linear sequence, but they are indeed regarded as separate phases of the same design process (Rauth, Köppen, Jobst, & Meinel, 2010) in which designers combine different approaches and successfully develop a solution. For this particular paper, emphasis will be placed on the ideation phase of Co-design.

2.5 CO-DESIGN

Similar to Design Thinking, Co-design does not follow a linear structure and it is generally described as a five-stage process (see Fig IX). Co-design and the five-step process is an approach that supports the design thinking process.

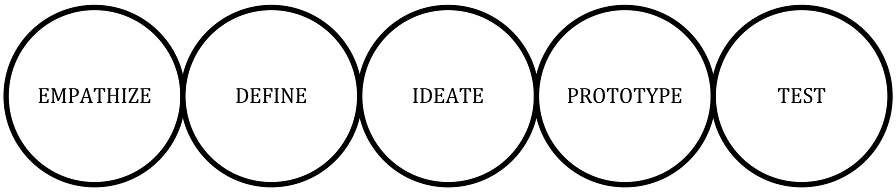

Figure IX. Co-design process. Adapted from the Institute of Design at Stanford (https://dschool.stanford.edu/).

Co-design is the act of creating with a group of stakeholders during the design process in order to meet the end-users' needs early in the process and ensure the usability of the ideas generated through the entirety of the design project. It is argued that including diverse stakeholders during Co-design leads to better solutions thus improving design outcomes (Yoo, D., Huldtgren, A., Woelfer, J. P., Hendry, D. G., & Friedman, B. 2013, April).

Because design does not come naturally to everyone, it is a complicated process that requires a certain skill set and mindset. When working with non-designers, the challenge for the designer turns into how to successfully transmit design thinking practices to the rest of the group. Co-design can help to overcome this challenge. Within Co-design, creative approaches of thinking and interacting with the Co-design participants have become an integral part for the design industry, where designers can generate tools for non-designer participants in order for them to be able to express themselves more creatively (Sanders et al. 2008).

In the traditional model of user-centered design, users were considered non-experts who provided direct feedback to a designer, an 'expert,' who then analyzed their feedback in order to come up with a new design. (Sanders et.al .2008). In contrast, Co-design practice considers the user as a partner who can provide insight based on their unique experiences while participating in activities related to ideation and conceptualization (Sanders E.B 2008). Elizabeth Sanders stresses that the end user's active involvement in the Co-design process can enhance a group's collective creativity between non-designers and designers (Sanders E.B 2008).

Co-design puts major focus on generating a design *with* participants rather than *for* participants (Sanders E.B. 2008). There is an important distinction in terms of how the designer approaches these two scenarios. Co-design involves the continuous assessment of a design challenge, which forces designers and non-designers participating in the experience to redefine the problem. The mutual participation and input of the Co-designers will inevitably alter the conception of one or various solutions— this usually takes place during the ideation phase of the design process.

2.5.1 IDEATION PHASE

Ideation is part of the creative process of design where ideas required to solve a problem are generated (Mueller, R. and Thoring, K). Ideation is commonly defined as "the process of generating a broad set of ideas on a given topic, with no attempt to judge or evaluate them" (Nielsman Norman Group, 2017). This phase focuses on generating ideas by initially concentrating on *quantity* instead of *quality* even though the ultimate goal is to achieve a high-quality design that solves a specified design challenge.

During the stage of ideation, participants in the ideation session will come up with as many ideas as possible, although some ideas will end up discarded, others will become potential solutions. The main focus of this part of the design process is to explore new approaches and angles for solving a design problem. It is commonly described as a phase where participants are encouraged to think outside the box. To maintain positive and fruitful engagement with participants, it is crucial that the experience remains judgment free. This is the best approach to promote innovation and spark creativity as the common understanding is that there are no wrong answers when exploring ideas (Basadur, M., & Finkbeiner, C. T. 1985).

Design Thinkers often use different ideation techniques borrowed from multiple creative disciplines such as game-storming (Gray, D., Brown, S., & Macanufo, J. 2010), brainstorming, and brain writing (Tschimmel, K. 2012). 3D printing has not been explored as a tool for ideation but this paper considers its potential for this aspect. Ideation tools are used to interact with participants, which may result in a better understanding of the problem and the user. The designer takes on the crucial role of efficiently translating the users' thoughts into design concepts that can be easily defined and communicated to the rest of the Co-design participants. During the ideation process, there might be a need to access alternative ways of thinking in order to move away from a linear problem-solving approach. This is especially true in Co-design environments where multiple disciplines are required to input their experiences and domain knowledge in order to understand the problem from various perspectives.

When it comes to multidisciplinary ideation, one of the most challenging aspects is combining ideas from scientists with different backgrounds and thus different ways of thinking. Generating ideas requires individual creativity as well as group creativity which is usually referred to as “collective creativity” (Sanders et al. 2008). Rosemary C. Reilly (2008) argues that creativity often accelerates when an interaction occurs between novice and expert participants through in-depth, realistically simulated activities, rather than superficial activities. Creating different levels of engagement with the user is then bound to produce a greater creative outcome according to Reilly (2008). In her research, Reilly reported how novice participants in their own domain could be as influential in the design process as expert users when engaged collectively in a design group. When group ideation is taking place with participants from different disciplines with different expertise, novice participants can be creative by engaging in collaborative processes of ideation and interactive engagement with other more expert participants to make sense of their own experiences. This paper will explore how the 3D printer can facilitate group ideation and engage expert and novices in interactive ideation experiences.

Through group ideation, Design Thinking has become a human-centered innovative process to tackle real-world problems through creativity. Using and generating creative tools to engage groups of participants could determine better solutions for designers in positions that require higher levels of engagement and creative thinking.

2.5.2 TOOLS FOR CO-DESIGN IDEATION

Co-design differs greatly from the traditional user-centered approach by enabling responsive participation from stakeholders to gather input continuously and iteratively, similar to rapid prototyping methods (Penuel et al. 2007). The tools and techniques used for Co-design have been developed and adapted to suit different contexts and project goals (Sanders, Brandt, Binder. 2010). These tools can take the shape of two-dimensional activities such as sketching or photo collaging or three-dimensional assets such as prototypes.

A commonly used tool in co-deign is the use of activities with rules, roles, and materials to allow participants to jointly construct solutions through tangible objects like prototypes and mock-ups. This type of tool brings non-designer participants with different background and experiences together and pools their creativity to address their collective design challenges (Buur and Bodker, 2000).

Some techniques of Co-designing lean towards creating more fun and playful environment. These playful techniques, such as role-playing and game-storming, allow unexpected perspectives to surge from the participants' belief that they are in the specific scenario for which they are developing ideas.

Figure X. Design game: Co-design participants use game pieces on a plant layout to discuss the instrumentation of present and future wastewater plants. Reproduced from "The design collaboratorium: A place for usability design" Bødker, S., & Buur, J. (2002). ACM Transactions on Computer-Human Interaction (TOCHI), 9(2), 152-169.

In the traditional approach to Design Thinking, these tools are used during the ideation stage. For example, Tim Brown, CEO of celebrated innovation and design firm IDEO focuses on understanding the user via the usage of tools such as ethnographic investigation, mind-mapping, storyboards, scenarios, improvisations, brainstorming, and rapid prototyping. The idea is that these tools can be effective in making ideas tangible. By making ideas tangible the creative engagement of the participants in the design experience is enhanced, producing better results in less time (Brown, 2008).

Table 1 - Tools for Co-design

INTERACTIVE ACTIVITIES	DISCUSSION ACTIVITIES	PHYSICAL TOOLS (2D AND 3D)
• Game boards and game pieces and rules for playing • Props and black boxes • Participatory envisioning and enactment by setting users in future situations • Improvisation	• Stories and storyboarding through writing, drawing, blogs, wikis, photos, video, etc. • Diaries and daily logs through writing, drawing, blogs, photos, video, etc. • Cards to organize categorize and prioritize ideas. The cards may contain video snippets, incidents, signs, traces, moments, photos, domains, technologies, templates and what if provocations.	• 2-D collages using visual and verbal triggers on backgrounds with timelines, circles, etc. • 2-D mappings using visual and verbal components on patterned backgrounds • 3-D mock-ups using foam, clay, Legos or Velcro-modeling • 2D and 3D prototypes

Note. Adapted from “A Framework for Organizing the Tools and Techniques of Participatory Design”, Sanders, E. B. N., Brandt, E., & Binder, T. (2010, November). In *Proceedings of the 11th biennial participatory design conference* (pp. 195-198). ACM.

2.5.3 EXAMPLES OF TOOLS USED IN CO-DESIGN IN THE FIELD OF MEDICINE

An example of Co-design tools, such as low fidelity prototypes being used in the field of medicine and healthcare, is the case of the Whittington

Hospital Pharmacy's approach to re-design a better pharmacy service for clients and staff. A design studio alongside a chief pharmacist at the hospital approached this challenge by enabling a collaborative environment in which participants were able to collaboratively re-design the workspace that would best fit their daily activities. This case study published by Design for Europe (DFE) describes how challenging it was to improve the current design. Previous efforts had already taken place in the form of direct questionnaires but had resulted in poor levels of user-participation, thus generating not very insightful information for design. The project started by organizing a series of workshops with multidisciplinary participants and end-users of the pharmacy, such as patients, management employees, staff and architects. Together they identified how the overall experience of visiting the pharmacy could result in anxious and uncomfortable feelings from the patients and the pharmacy's actual setup.

The facilitators of this experience introduced main, central design concepts to the participants resulting in large groups engaging in idea generation and sharing of the problems' perception. These activities produced a shared understanding of the problems' definition and helped establish a consensus of the areas that needed the most attention. Defining the problem and identifying the focused challenges aimed to encourage the participants involved to explore the role of objects, furniture and design in their workspace in order to better understand the impact and role these factors have in their daily activities and behavior. By bringing participatory elements together through facilitated workshops and most importantly the use of prototypes, they improved the overall experience of the end-users. By using physical low-fidelity (i.e., cardboard) tools to generate mutual understanding of the space and to explore the possibilities of new interior design set-ups, the Co-designers came up with newly generated ideas. They tested those ideas in small scale models (i.e., early prototypes), eventually scaling up the design to be tested in the pharmacy itself.

These playful experiences and participatory environment provided extended feedback and insights from lessons learned through the design experience, and previously identified experiences. As a result, new areas in the pharmacy were introduced while other areas were redesigned. This reportedly improved the end-users' experience visiting the pharmacy, increasing employees morale and eventually boosting sales (TILT studio, 2014). Other areas of the hospital have since taken an interest in using this design approach to re-design other spaces.

Figure XI. Studio TILT's codesign and prototyping process in action at the Whittington Pharmacy Screenshots from "The Whittington Pharmacy Project" DFE Vimeo Channel, video by Studio Tilt published on April 21, 2013.

In the case study described, two main attributes were identified as key to the success of the project. The first one was having someone central to the pharmacist point of view, which understood the project and held distinctive domain knowledge. This key player in the Co-design experience not only helped with identifying challenges from an end-user perspective, they also helped facilitate the exercises and convince other participants to engage. The second attribute was the interest and engagement of the participants, which resulted in effective feedback and idea generation created while interacting with the prototypes developed by the team (TILT studio case study 2014). This case made use of low fidelity prototypes to generate solutions which worked in their environment, an approach sufficiently adequate enough for this type of participant. Scientist neurobiologists, on the other hand, require higher fidelity prototypes that offer greater usability and functionality to simulate their environments and relate to their work.

2.5.4 EXAMPLES OF 3D PRINTING IN CO-DESIGN

Ideation in Co-design with participatory approaches focuses attention on the initial phases of solving a problem where designers have to move from initial understanding of the challenge to idea generation and concept design. There are cases where 3D printing technology has allowed this transition in the design process to be addressed in a more cost and time effective way by enhancing the Co-design environment and allowing the user to become a more vocal participant throughout the experience.

An example of 3D printing technology being used as a communicative medium in the context of Co-design is the development of a Multisensor Co-design support tool for smart connected things developed by a group of students at the Faculty of Computer Science in Chemnitz, Germany (Lefeuvre et al. 2016). The team developed this support tool using a low-cost 3D printer to support the early design process in a Co-design environment by focusing on the ideation, and idea generation phase with the final goal of developing smart products for creative applications.

The project is known as “Loaded Dice” and consisted of two cube dice wirelessly connected and powered by Arduino microcomputers. While one of the dice was built with a different sensor on each of the faces, the other would house different mechanical actuators on its sides. The two devices were designed to carry functional values through visual and haptic sensors (Lefeuvre et al. 2016). The Co-design approach taken in this example was to create a tool which would allow users to experience difference sensorial inputs with the random shuffling of both dice by serendipity.

Although the overall goal of this project was to create better versions of future products for the end-user, the project initially focused on facilitating the users experience participation as Co-designers. It did so by creating interactive and supporting tools to take part in the Co-design activities, combining advance technology and serendipity to collect valuable insights from the participants that otherwise would have remained hidden (Lefeuvre K. et al. 2016).

There were two main objectives in the approach taken through this type of collaboration. The first one was to enhance the active participation of users by engaging interactively with the functions of the sensor and the actuator dice. The second objective was to co-create value through Co-design tools (prototypes) and support the collaboration of participatory methods of design. This study focused on the benefits of 3D printing for creativity and idea generation rather than validating an already designed idea, similar to the case study explored in this paper.

Another very crucial benefit of using 3D printing technology in Co-design environments is that it makes it possible to design innovative, creative, and functional solutions by engaging in user continuous experimentation with 3D printed objects. Continuous user experimentation enabled by 3D printing has led to the exploration of new opportunities to improve Co-design by enhancing the idea generation phases of participants. This has increased participation level, creating further inclusiveness for the practice of Co-design (Payne et al.2008). The research of Vasilis Kostakis et al. (2015), explores how 3D printed physical tools can help students to think differently than they did previously, and as a consequence, see the world differently. Specifically, they consider the impact of 3D printing as a tool to educate and learn, as well as its use as a meaningful inclusive communication asset between blind and non-blind students. The 3D printer was used by the non-blind students to create physical representations of chemical molecules for the blind students to interact with and learn from (Kostakis V. et al. 2015). The 3D printer, in this case, was used as a tool to enable inclusivity in design and educational practices. In this example, not only the benefit of inclusivity is showcased, but it also engages participants (in this case, students) to generate cognitive reactions to a prototype. Generating ideas and transmitting knowledge through the empathic touch and interaction with 3D printed objects are used as a tool for ideation and Co-design.

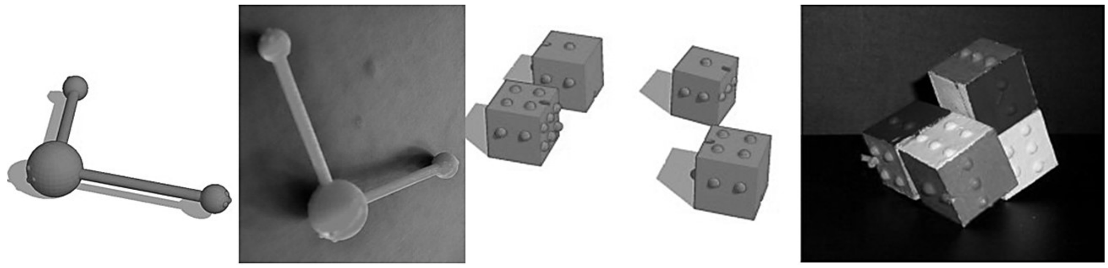

Figure XII. (left) Kostakis et al. (2015). 3D printed molecule designed on CAD by non-blind students for blind students. 3D printed molecule Kostakis et al. (2015). (right) 3D design of braille dice, 3D printed braille dice with painted sides for non-blind students

Matching the innovative approaches and simplistic style of the Scandinavian furniture retailer IKEA, IKEA Israel has started a collaborative project with a non-profit organization to generate a wide range of 3D printable furniture upgrades to assist people with disabilities. The projects go by the name of ThisAbles, and it is a cutting edge approach to inclusion and accessibility being explored and enabled by 3D printing and design.

These examples have shown that 3D printing has become a powerful tool to enable experimentation in various fields, bringing engineers, designers, scientists, and creators together and ultimately improving products and Co-design experiences. For designers, 3D printing helps to tackle the critical challenge of finding appropriate tools and ways of engaging with the users or scientists involved in the design challenge. This technology presents a better approach to synthesize ideas generated through the design sessions through the use of prototypes and physical objects. For scientists, collaboration through 3D printing resources facilitates thinking practices and allow participants to visualize, learn and test their ideas, to increase and further developing the creative process in order to generate the better design.

2.6 SUMMARY

In summary, the literature review has shown that the rapid growth of

3D printing technology over the past several decades has enabled great advances in the science field. For low budget laboratories, the use of low-spectrum 3D printers allows scientific researchers to address their design challenges by customizing equipment to their needs. In general, scientists are used to solving problems from an analytical point of view in contrast to the multi-linear and laterally approach designers tend to employ. The difference between scientists and designers is that the former follows a scientific method or a problem-solving behavior in order to find the nature of what exists, while the latter uses an alternative approach to solve problems by inventing things of value which do not yet exist in order to figure out the best solution. While deductive and inductive mindset reasoning may be adequate for linear problem-solving approaches, the creative solution might need to be supported by abductive types of reasoning which allow imagining what does not exist yet rather than reasoning based on what is presented as obvious evidence. This can limit the ability of scientists to think outside the box and find creative design solutions to make more suitable lab devices.

Through the use of Design Thinking and Co-design approaches, scientists may get benefits from the experience of interacting with tools and domain knowledge brought by the designer to trigger their own creativity. There are various tools discussed in the literature that can be used to trigger the creative ideation process in non-designers or scientists, such as affinity diagrams, brainstorming, prototyping, etc. However, the exploration of how the 3D printer can help facilitate this creation process has not been fully discussed yet. Currently, the majority of the literature on 3D printing in the design field focuses on its benefits in manufacturing and prototyping for idea validation rather than ideation. The following case study aims to explore this underdeveloped area and better understand how the 3D printer can aid the ideation practice in a multidisciplinary Co-design environment.

3. CHAPTER III – METHOD

3.1 BACKGROUND

For the past year, I have been working with a team of scientists at the Department of Cellular and Molecular Medicine in the University of Ottawa. As a designer, my interest in collaborating with diverse disciplines has pushed me to work closely with the scientists in order to understand their unique perspective and insights. Over the past year, the scientists have shown increasing interest in the potential of the 3D printer and the design process. Several projects were developed to explore the fruit-fly behavioral patterns using the 3D printer as a primary tool to generate the equipment. These projects, which have been partially inspired by the possibilities and benefits the 3D printer, opened a new range of possibilities for cellular and molecular scientific research, allowing for enhanced customization, automation and development of new “science kits” that can potentially help scientific research.

During the experience of collaborating with the scientists, I noticed how foreign the concept of the design process was to them. Initially, scientists would just imagine a science kit that would allow them to explore their research, without taking any interest in the process to reach that desired kit. It was noted that gradually, the disinterest in the design process decreased as participants became more engaged through the use of 3D printed prototypes. Simultaneously, their engagement with the designer and the 3D printed objects started to clarify many of the problems that initially were not discussed either because of the lack of communication skills between parties or simply because they were hidden needs and not considered.

This experience sparked my curiosity and led to my research question: *"How can 3D printed objects facilitate the process of mutual communication and collective idea generation between scientists and designers in order to aid in the generation of new or refined ideas and uncover hidden needs to further the design process".*

To address this, a small workshop was organized at the University of Ottawa Cellular and Molecular laboratory in order to engage participants in my research question. The main focus was put on the multidisciplinary and collaborative aspect of ideation practices and the ability to generate ideas during the design process. The goal of this project was two-pronged. Firstly, it focused on exploring the potential of the 3D printed objects to enhance the ideation and participatory practice in Co-design contexts. Secondly, the project was designed to successfully Co-design a piece of equipment necessary for the scientists' fruit fly behavioral research.

The approach taken in this case study introduces the 3D printer in a slightly different way to stimulate user participation and enhance collective creativity during the ideation/prototyping phase of the design process. It aims to demonstrate how 3D printing can be used effectively to help scientists and designers engage in creative development rather than using the technology to validate ideas as prototypes and for further manufacture uses.

The idea of introducing functional 3D printed prototypes, instead of any other type of prototyping, was that a highly functional prototype would be able to integrate the user and scientists experience and help stimulate collective creativity by confronting the user with a realistic simulation of the product idea or concept, based on their own assumptions and ideas. Combining this exercise with commonly used design techniques in a Co-design context, such as brainstorming, sketching and post-it noting was expected to further foster the engagement of the participants, in order to generate the ideas that would turn into early prototypes. These prototypes had the role of exploring diverse scenarios in which the end-user would use the product, and provide a medium to communicate ideas and insights.

The design challenge introduced in the workshop was to develop a tool to house and record flies. The newly designed equipment would allow the lab to manage and collect data from the fruit fly in a more effective way, thereby freeing an immense amount of time that technicians spend when using non-specific or improvised equipment to do the job. In general, 20% of the technicians' daily work was dedicated to this manual task. It was challenging for the technicians to handle the specimen and constantly repeat the study with multiple groups of flies. The general agreement was that fruit flies specific product was needed so that management of the specimen would be easier. In addition, it was required that the tools be able to handle more flies and offer a user-friendly product use cycle. Tools and artifacts that were not specifically designed for fruit flies or these type of experiments were previously used by the lab to attempt to resolve this challenge. However, none of them completely satisfied the laboratory needs. These prior designs were taken into consideration as a base for the workshop because it provided insight into the scientists thinking.

3.2 METHOD STRENGTHS AND LIMITATIONS

A case study approach was selected as the main method to explore the research question for several reasons. Firstly, case studies have a proven record of bridging the gap between theory and practice. The research question explored in this paper is how the theory of Design Thinking translates into practice through the use of the 3D printer.

Secondly, case studies allow the researcher to immerse themselves in the environment and culture. For this research, it was beneficial for the researcher to be embedded as it was an unfamiliar subculture (i.e., scientists) which required the designer to better understand how things are typically organized and prioritized in this environment. It also assisted the researcher in understanding how scientists interrelate and the unique cultural parameters they follow. It was important for the researcher to identify what the scientists and technicians (i.e., non-designers) categorized as important in their workplace (i.e., organization, cleanliness, habits, etc.) to better understand their design requirements.

Thirdly, case studies allow data to be collected from direct observations of an individual or group involved. Information about input processes can be identified through this type of observation, and it can show the road taken to specific results being generated. Observations in a case study make it possible for other researchers to replicate the results uncovered by this method. For this research project, observation of the participants' interactions with each other and the 3D printed objects was important to understand their value and influence in the ideation process.

Fourthly, case studies allow for multi-perspective analysis, meaning that the researcher can consider the individual perspective of multiple actors and the interaction between these. More specifically, it allows silent participants to voice their opinion and empowers them to participate. In the context of this research, several different disciplines were included in the project requiring an analysis of multiple perspectives.

Finally, the case study approach can provide insight for future researchers looking to understand similar situations by shedding light on aspects of behavior and human thinking that would be impractical to study with other approaches. In this instance, the case study approach is used as a tool to approach exploratory research, a way to generate new ideas and a way to illustrate theories that can help show the different aspect of a group of persons, an activity or a relation in the participants' environment.

A limitation with case study methodology is that broad generalizations are not possible since they tend to focus on specific cases. This research project takes into consideration this limitation and recognizes that further tests would be needed to complement this research and make definitive claims. The case study approach is still valuable in this context, however, because it allows for an in-depth investigation of a very niche area that has not yet been explored.

The case study will begin with a detailed description of the design project followed by a chronicle of the two phases of the workshop and individual interviews. Qualitative data was collected through multiple sources, including first-person observations, notes, documented sketches, physical material prototypes, and Co-design tools such as brainstorming, in addition to the interviews.

3.3 DATA COLLECTION

Several sources of data were employed throughout the case study to triangulate information and ensure a more robust analysis. These sources included:

3.3.1 INTERVIEWS

Semi-structured interviews were conducted with participants following the end of the workshop to gain an understanding of their experience during the Co-design sessions and garner insights as to the role of the 3D printed objects. Through the interviews, each participant was probed individually about the sessions in order to provide insights into the multidisciplinary perspectives of the research question. For example, they were asked about their views on using the 3D printed objects and how it helped their ideation process. Interviewees were audio recorded, with their consent, to allow the researcher to capture all information and reduce the possibility of the researcher misconstruing their opinion.

These interviews focused on the participants' experience with the 3D printed objects targeting idea generation practices. The interviews also included information about previous experience with 3D printing and expectations from the technology in this context. The interviews lasted ten to fifteen minutes and were transcribed verbatim. In addition, implementations for future designs were discussed in an informal meeting after the interviews individually. The findings from the interviews and workshop were used to create a series of further suggestions for the continuation of the design process. Although finalizing the design was not central to the workshop, a compilation of ideas to solve the challenge was created to support further development of the tool. Also, the findings from the workshop were validated through these interviews and after discussion with the end-users.

3.3.2 DIRECT OBSERVATION

Direct observation by the researcher/ designer occurred during the two workshop sessions. Video recordings of the Co-design sessions were taken to document the sessions and allow the researcher to reflect on the conversations and interactions between participants. This was crucial as the researcher was also fulfilling the dual role of designer during the sessions which split the time between observation and interaction. Recording the videos also helped the researcher to be as unobtrusive as possible.

During the ideation sessions, small interventions by the designer were required at times to keep the session on track and flowing. By becoming an active participant, the designer/ researcher developed participant observations as well. This is a common practice undertaken by researchers when studying groups and provided the researcher with the opportunity to collect further information. Measures were taken to reduce the potential that the involvement of the researcher might alter the course of events. For example, the researcher held back opinions on the design ideas generated by the participants to reduce their bias and encourage their own ideation practice.

3.3.3 PHYSICAL ARTIFACTS

Physical artifacts produced during the first phase of the workshop, such as drawings and notes, were collected and analyzed. These artifacts played an important role in identifying themes of focus during ideation. It also provided the researcher with the chance to identify unique interactions and insights on the participants' engagement with the objects.

3.4 SETTING

The laboratory in which the case study took place was located in Roger Guindon Hall at the University of Ottawa, Canada. Specifically, in the fruit-fly neurobiology lab under the Department of Cellular and Molecular Medicine. The scientists at this laboratory engage in the very niche field of research on neurobiology using the common house fruit-fly as test subjects. Different aspects of this specimen behavior are studied through the observation of certain methods and patterns, such as mating, feeding, and in this case, motor skills. These methods range from genetic alteration to experimenting with simple motor skill challenges. While there are other laboratories internationally looking at this area of research, it is one of the only ones in Canada.

There was not a specific space provided to perform the Co-design workshop sessions as the laboratory spaces were already designated. The area where the workshop was held was in a conference room in Guindon Hall building at the University of Ottawa. There was a white-board located in the conference room which allowed participants to sketch and write notes, and a big table to sit around. Overall, any space could have been used for this workshop, as long as it allowed the participants to face each other and place materials such as pens, paper, and prototypes in a table for discussion.

Figure XIII. (left) Photo of workshop space. (right) Materials provided for the workshop. March 20, 2019.

3.5 PARTICIPANTS

A small number of participants, including one technician, two neurobiologists, and one engineer were involved as core-users, which in this paper are regarded scientists. Participants from different disciplines (i.e. Engineering, Computer Science, Biology) who had previously worked in developing products, tools, and assays to assist the fruit-fly related research were asked to volunteer for the workshop.

There were several considerations involved in the selection of the group of participants for the Co-design workshop sessions. The designer/researcher was not in control of most of these selection factors. Instead, they were largely determined by the individual’s roles, technology expertise, and time availability.

For the factors within the control of the researcher, the following criteria were used for the volunteer participant selection:

- The head and the most knowledgeable participant would be in charge of framing the specific needs of the project.
- Participants could be selected to participate during the first Co-design workshop session and not the second phase, or vice-versa.
- The technician with the most developed skill-set would take part in both Co-design sessions.
- The less skilled participants would be used as end-users to try prototypes after the first ideation session.
- The design could focus the design in a solution for a specific issue and later on the prototype.

There was no ranking on which of these criteria was most important, and the appropriate list of criteria was carefully considered during the actual project when establishing the group participants for the sessions. In this case, however, the first criteria were the most important as the head and most knowledgeable participant was the neurobiologist in charge of the research, but not the end-user. He would not be using the tools to perform the daily tasks, although he knew exactly what was to be expected of its use.

As a note, none of the technicians or head neurobiologist had any proven experience in 3D printing, and they all relied on third-party companies to design customized lab-ware equipment for the lab in the past. Although some showed great interest in CAD modeling and 3D printing, limitations in their schedule rendered it impossible for them to learn even the basics of this knowledge skill during work hours. The workshop sessions focused on ideating instead of 3D modeling and printing.

The participants were explained how the design development would take two workshops sessions to be completed and at least two hours would be required for each session. They were also explained the dynamics of some of the activities that would take place, and they were reminded that this Co-design experience would rely on their participation rather than an individual intervention by the designer.

3.5.1 SCIENTIST

The head neurologist, who had all the technical knowledge about fruit flies, was in charge of giving focus to the project by framing what types of behavior were being studied and for what reason. This provided a wider perspective for the team members that were not familiar with the research being developed (i.e. the designer, engineer and some technicians). As the most domain knowledgeable team member, the neurobiologist provided direction and specific insight on the non-human participant (the fruit-fly), and framed the problem as an overall scientific challenge, measuring the climbing ability of genetically modified flies. The head neurologist’s participation in the Co-design sessions was intermittent due to work-related constraints. Regardless, his insights and participation helped determine the design challenge to be explored in the workshop.

3.5.2 TECHNICIAN

The technicians' job was to manually insert flies into the non-fruit fly specific product. They had to organize five to six groups of flies and secure them, then they would tap the groups into the table throwing the flies to the bottom of the tubes holding them. They would then measure and count how many flies crossed a marker line in a specific range of time.

Every technician's experience was different and they were expected to identify different problems when working with the non-specific fruit fly chamber. This helped as a starting point in the Co-design sessions to identify the conflicts presented and to understand how they as users understood the challenge. Although the technicians and head neurologist differed in cultural origin, all seemed to share the same environment culture in the laboratory. Race and ethnicity were considered a non-influential factor to be considered in the workshop. The age of the participants was also not considered an influencing factor to the project as all would have similar experience in performing fruit-fly related activities. The technicians were in the same age range of 24-32 years old and all shared a similar background in neurobiology or biology.

The only requirement these participants had to meet was that they were familiar with the fruit-fly laboratory environment and that they had taken part in the development of any of their products or assays. Their different levels of experience were regarded as an advocate of sharing different expert perspectives on the same subject.

3.5.3 DESIGNER

The role of the designer was to observe the participants and facilitate the sessions simultaneously. The designer was also in charge of managing the 3D modeling and prototyping of ideas resulting from the initial Co-design session, a secondary role performed outside the scope of the workshop.

In order for the designer to properly collect data and move forward in the Co-design process, several questions need to be addressed, such as: How functional should the prototypes be to successfully simulate an experience? What should the output of the sessions look like (i.e., Prototypes? Full solutions? Ideas?) What is the main purpose of collaborating in these sessions? How can the expectations of the participants be managed?

In this case study, the designer would only participate as an observer and facilitator as opposed to being an active participant. The backstage phase of the Co-design sessions (when the 3D model was digitized and printed) or the time in between phases, required design experience in order to translate the ideas and information from the scientists into a printable object that reflected the needs of the participants.

3.5.4 NON-HUMAN PARTICIPANTS

The specimen used in the laboratory is the Drosophila melanogaster, otherwise known as the common house fruit fly. This small animal is important for scientific research because it allows the researchers to target certain specific behavioral patterns that can be related to human conditions. The common fruit fly provides scientists with the opportunity to expand further and develop genetic research.

Table 2 - Participants breakdown

PARTICIPANTS	NUMBER	AGE	GENDER	ROLE
Technicians	1	25	Male	End-user Participant
Engineer	1	24	Male	Participant

Neurobiologist	2	32-45	Male	Lead scientist Participant
Designer	1	28	Male	Facilitator 3D modeler 3D print Participant

3.6 PROCEDURE

It was important for the participants involved in the workshop to establish a common understanding of the goals of the design process, the status of the actual products, and the role of prototyping throughout the overall design process.

The Co-design workshop was conducted in two phases. Although both of these phases would take place in the laboratory, the activities performed on each would differ greatly. The first phase would focus on generating a collaborative experience where the scientists and designers would participate in different ideation activities (i.e., brainstorming, post-it notes, sketching) to identify the problem and generate ideas that would be translated into 3D printed objects. The second session of the week would have the goal of engaging with these 3D printed objects and work-like simulation settings, allowing participants to generate further ideas and refine their design solutions. This would allow the expertise and insight of scientists to be developed practically. The experience focused on enabling quick identification of issues whenever there was a clear failure or breakdown on the prototype, resulting in more solutions to be generated.

3.6.1 FIRST PHASE WORKSHOP

The first phase of the workshop covered two important aspects of the design process: inspiration and ideation. The inspiration phase mainly focused on better understanding the end-user and participants' needs and challenges when using their current fruit-fly climbing assay tool. A series of facilitated discussions and exercises took place with the objective of identifying the current condition of the fruit-fly climbing assay. Participants had the opportunity to share their experience, thoughts, ideas about the challenge, barriers, limitations, and opportunities in order to Co-design a simple effective solution to the problem. Participants used notes, sketches, and discussion to do this. They were expected to input these insights from their point of view based on their personal and professional background. This was done with the hopes of gathering multidisciplinary perspectives in the session that would help develop ideas to solve this unique challenge.

Initial discussions identified three main themes that required ideation: functionality, usability, and simplicity. It was determined that the first design requirement was that the tool to be able to strengthen the users' ability to operate the fruit-fly climbing tool in their environment properly and manage a certain number of specimens. A sturdy but simple non-mechanical solution was to be conceived to address usability. The second design requirement focused on supporting the experiment by providing measuring and marking tools required to examine the distance that the specimens climb, which could be addressed with a diverse range of solutions. This required ideation on functionality. Simplicity was identified as an important consideration in both requirements.

For the ideation part of the workshop, office materials (e.g. paper, pens, post-it notes) were provided to the participants to discuss potential solutions and attempt to communicate them to the team. A facilitated breakout discussion was conducted to discuss potential solutions to the identified problems. The number of ideas generated during this phase was adjusted and refined through discussion and further ideation processes by the Co-design group. The head neurobiologist, and the rest of the technicians who engaged in the practice of the fruit-fly assay validated the applicability of these ideas to the lab environment. Although the ideas generated in the first phase were not completely defined, they followed the agreed upon themes of usability, functionality, and simplicity. The ideas were ranked according to their relevance to these themes and the top ideas were selected for the next phase of the workshop.

Figure XIV. (left) First workshop session. Lead scientist explaining the goal of the fruit-fly assay. (right) Participant using the original product to explain some of the design challenges. March 20, 2019.

Table 3 - Agenda for Phase One of Workshop

AGENDA	TIME & DURATION	EXPLANATION	TOOLS/METHOD	DATA
INTRODUCTION - DESIGN BRIEF	DAY 1 - (20min)	Participants were introduced to the workshop and objectives were outlined.	Open observation strategy	Field notes

PROBLEM IDENTIFICATION (INSPIRATION PHASE)	DAY 1 - (40min)	A facilitated breakout discussion was conducted to identify the problems.	Visualized ideas, Dialogue tools	Observations, field notes, dialogue
PARTICIPANTS IDEATION (IDEATION SESSION)	DAY 1 - (50min)	A facilitated breakout discussion was conducted to discuss potential solutions to the identified problems.	Paper, pens, post-it notes, brainstorming.	Sketches, field notes, observations
WRAP UP AND MOVING FORWARD	DAY 1 - (10min)	Selection of best design solutions and discussion of next steps.	Post-it notes	Field notes

3.6.2 3D PRINTING PERIOD

The actual 3D modeling and printing were carried out by the industrial designer on the basis of the ideas generated throughout the activities and the specific knowledge, specifications, and prototypes created by the Co-design team. This phase was not a part of the workshop and it took place off-site. Only the designer was involved. The goal was to gather the insights and ideas generated from the first session and translate that information into physical 3D printed prototypes in order for the participants to engage in 3D printed related ideation practices in the second phase of the workshop.

The total printing time allotted for the ten early prototypes was seven hours. It was initially thought that modeling the ideas through CAD software would take a significant amount of time, but in reality, because of the simplistic nature of the project, the ideas conceptualized by the participants were easy to represent and did not take more than 3 hours to design. During this period, the designer/researcher was able to interpret the participants' notes and sketches and translate that information into 3D models.

The main challenge for the designer/researcher during the 3D printing phase was to remain neutral and not suggest further solutions based on the first round of ideas. The ideas provided by the participants were not yet fully complete and it was challenging for the researcher/designer not to inject their own experience as a designer to further refine the participants' input. To maintain the integrity of the experiment, no modifications to the initial designs were performed by the researcher/ designer.

3.6.3 SECOND PHASE WORKSHOP

The second phase of the workshop focused on having the participants interact with ten 3D printed prototypes generated by the designer following the ideation session in the first phase of the workshop.

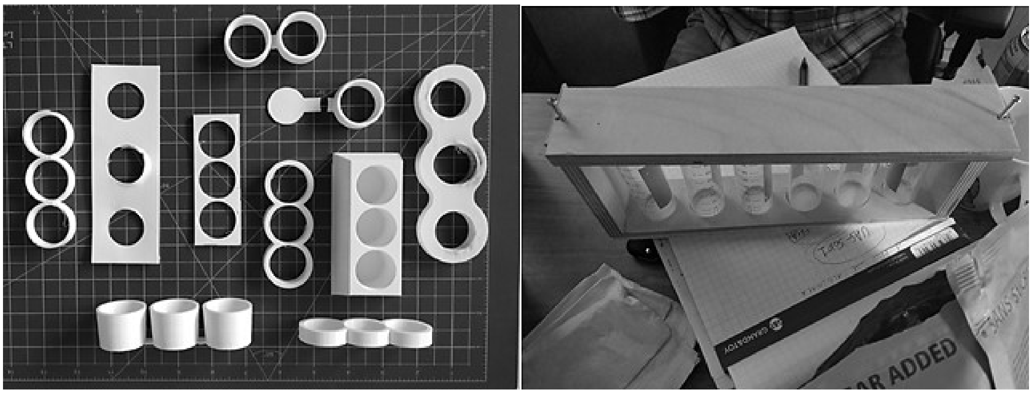

Figure XV. (left)Ten 3D prototypes resulted from initial ideation with participants.(right) close up of original product holding fruit-fly tubes. March 21, 2019.

In order to explore how these 3D printed objects would influence the ideation process, the designer refrained from modifying or tweaking the design ideas from the participants. In total, ten 3D printed pieces were provided to participants to explore their interaction and ideation process. Some of the 3D printed pieces shared the same design idea but differed in measurements in order to address the aspect of functionality, enabling them to simulate their work experience.

Participants took a hands-on approach to test, break, combine, explore, and imagine further ideas taking their initial concepts (which were in a physical state) as a basis for design. This activity was further supported by brainstorming, sketching, and field note observations from the participants, which resulted in further categorization and synthesis of the ideas generated. To conclude the second phase of the workshop, participants identified a series of improvements for the final product based on the initial themes: functionality, usability, simplicity. For example, while interacting with the 3D printed objects, the participants realized that there were additional design challenges they had not previously considered such as the ergonomic factors that affected the use cycle. Also, participants were able to compare and contrast their initial ideas and ideate on ways to incorporate the best aspects of each design.

Figure XVI. (left) Scientist stimulates and explains the steps of assay. (right) Participants interact with different 3D printed objects mimicking the scientist. March 22, 2019.

This second phase of the workshop was followed by semi-structured personal interviews, which also took place in the laboratory context, to gain a better understanding of their experience with the 3D printed objects.

Table 4 - Agenda for Phase Two of the Workshop

AGENDA	**TIME & DURATION**	**EXPLANATION**	**TOOLS/METHOD**	**DATA**
INTRO TO PROTOTYPES	DAY 2 - (10min)	Discussion of the activity to be conducted with the 3D printed prototypes.	N/A	N/A
PROTOTYPE ENGAGEMENT (SECONDARY IDEATION SESSION)	DAY 2 - (60min)	Participants were given time to explore and interact with the 3D printed prototypes and encouraged to ideate.	3D printed prototypes Post-it notes, pen, paper, brainstorming, sketching	Video and audio recording
FUTURE DIRECTION & WRAP UP	DAY 2 - (10min)	Discussion of the best ideas generated in the second phase and the future design alternatives.	Paper, pen, post-it notes Facilitated discussion	Sketches, field notes
INDIVIDUAL INTERVIEWS	DAY 2 - (40min)	Personal semi-structured Interviews	Semi-structured individual interviews	Transcribed individual Interviews

4. RESULT

4.1 PHASE I FINDINGS

Data collected from the first workshop session, along with observations and field notes, revealed three main findings that can be categorized under the following themes:

- Divergent communication approaches
- Type of participation
- Vision vs. Reality

4.1.1 DIVERGENT COMMUNICATION APPROACHES

During the first ideation session, where no physical objects were presented other than the original tool, there was a clear difference in the way participants communicated their ideas. The engineer was clearly more comfortable sketching and exploring ideas through drawing lines on paper and whiteboards, while the scientist and technician focused on making bullet points and notes. This was observed by the researcher during the workshop and also confirmed later in the interviews with participants. The scientist and technician were not prone to materialize their ideas and preferred to describe their thoughts to the engineer who was clearly better versed in drawing techniques. This was a clear indication of the challenges of communicating ideas in multidisciplinary environments. The scientist, technician, and engineer had to take turns to explain their ideas affecting the flow of the ideation process. When the scientist or technician was encouraged to sketch or describe their ideas on paper, they would engage briefly but quickly go back to using bullet points and small notes to support the idea process thus detaching themselves from the exercise of sketching. In contrast, the engineer would attempt to draw technical sketches with measurements and additional notes to consider. The diverging approaches to communication impacted their ability to clearly articulate ideas across the disciplines and led to instances of confusion.

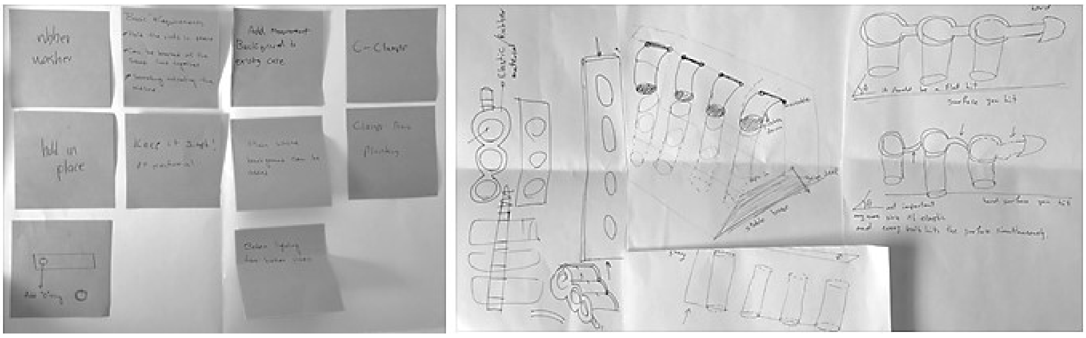

Figure XVII. Engineer ideation output (left). Scientist and technician ideation output (right). March 20, 2019.

4.1.2 TYPE OF PARTICIPATION

The scientist and the technician were eager to describe the fruit fly experiment they were working on but when it came to ideating on the design they felt it was not their role. They often turned to the engineer and designer to provide a solution rather than engaging in this thinking themselves. Although participants were willing to make an effort and engage with the sketches and ideation tools presented, the interest in continuing to explore ideas quickly faded. The lower level of participation from the scientist and technician could be related to their pre-existing assumptions about their role in the design process and that of the engineer and designer. They felt that their role was to describe the problem rather than engage in creative idea generation. The tools used in the first phase reinforced these pre-existing assumptions about their different roles in the creative process. The engineer relied upon sketching which was viewed by participants as a more creative outlet and concrete depiction of design, thus solidifying their role as the primary ideator.

4.1.3 VISION VS. REALITY

Participants were encouraged to look for outside sources for inspiration during the first stage of the workshop. For example, the engineer offered very complex suggestions and mechanisms like c-clamps and flexible structures based on their experiences and domain knowledge. This type of thinking and ideas, while common for an engineer, was considered “outside the box” to the scientists and technician. In contrast, scientists would offer solutions that were closer to what they already knew and could visualize. For example, they would often refer to existing equipment within the lab and suggest minor adjustments. Having multidisciplinary perspectives around the table pushed each participant to think about alternative solutions outside their own realm of thinking. While there were attempts to explore this “outside the box” thinking, the ideas generated often lacked realism and feasibility. Half of these proposed solutions were ultimately discarded by the scientist because of their high complexity.

4.2 PHASE II FINDINGS AND RESULTS

The second phase of the workshop was expected to reveal specific insights on how 3D printed objects can facilitate mutual communication and collective idea generation between scientists and designers. It was also intended to provide insight on how 3D printed objects can aid in the generation of new or refined ideas and uncover hidden needs to further the design process. Follow-up interviews with the participants revealed that they did not have any prior experience working with 3D printed objects, although the engineer expressed some familiarity with the concept. The results of the second phase of the workshop were consistent with these expectations and demonstrated that the 3D printed objects could play an important role in the creative process. Data collected through observation of the participants' interaction with the 3D printed assets and other sources, such as field notes, sketches, and follow-up interviews, revealed three findings on the effect that the 3D printed objects had on the ideation process. These can be categorized under the following themes:

- Enhanced communication through playful interaction
- Vision vs. Reality
- Identifying new grounds for ideation

4.2.1 ENHANCED COMMUNICATION THROUGH PLAYFUL INTERACTIONS

Introducing the 3D printed objects into the design process allowed participants to engage and play with their ideas. The participants each demonstrated different ways of engaging with the objects related to their own domain expertise. For example, the technician simulated his work with the 3D printed object and ideated based on this simulation. The engineer took the same prototype but focused instead on analyzing, testing and verifying the structural integrity of the object because that was considered most relevant for his work. The scientist assessed whether the object met the initial design criteria and made notes rather than simulating his work. As a result of engaging from different approaches with the 3D printed objects, they were able to ideate on different concepts at the same time. In addition, they were able to combine their ideas to create a more fulsome design. In contrast, during the first phase of the workshop, participants focused on single concepts because they did not have a medium to ground the discussion. The basic tools used in the first phase of the workshop created divides between participants because not all felt comfortable sharing their ideas through the same medium.

In addition, the activity of sharing their ideas through the interaction with the 3D printed objects became a mutual learning experience. The 3D printed objects were not only a way to represent their ideas but also a tool for communication. The learning process allowed them to sympathize with each other's ideas and made it easier to imagine scenarios that were not related to their expertise. For example, by mimicking how the scientist and technician perform the experiment with the fruit flies, the engineer was able to gain a better understanding of their design needs.

All participants showed a high level of engagement with the 3D printed objects and excitement to see their ideas become physical assets. The 3D printed objects broke participants out of their perceived roles in the design process and made them more comfortable discussing their ideas through play. Overall, the participants were more vocal about their opinions and findings than during the first phase of the workshop, especially the scientists, who found it easier to jump into the discussion while grabbing the prototypes.

Table 5 - Participants Interaction Breakdown

PARTICIPANT	TYPE OF INTERACTION WITH THE 3D OBJECTS	OUTCOME	IDEATION CATEGORY OUTPUT
ENGINEER	Testing and verifying the accuracy of 3D printed part with the ideas previously generated	Refinement and restructuring past ideas, generating new ones	Functionality Reliability
SCIENTIST	Focused on identifying solutions for the challenges by using the objects in trial and error	Identify new design challenges not previously acknowledged	Simplicity Functionality
TECHNICIAN	Focused on simulating work experience and playfully engage with 3D printed objects	Mutual learning experience and enhanced discussion. discovered new ideation grounds	Functionality Ergonomics Usability

4.2.2 VISION VS. REALITY

During the first phase of the workshop, participants struggled in designing adequate solutions because they did not have defined boundaries on what was possible and necessary. The simple tools used in the first phase could not transmit the complexity of their ideas clearly. The introduction of the 3D printed objects in the second phase of the workshop helped them realize the possibilities of their ideas by grounding expectations in a physical representation. In other words, the 3D printer demonstrated the feasibility of their initial ideas. In the words of interviewees, the 3D printed objects provided examples of their ideas in the real world, thus helping them create better insights on the future of the design and space for improvement. Their new ideas generated in this session were still “outside the box” drawing from their own experiences, but they were able to adapt these ideas more realistically because the 3D printed objects allowed them to reason. For example, in the first phase, participants developed ideas based on outside sources, but when they tried to relate this idea to the product, they had trouble explaining the applicability. In the second phase, when participants drew from ideas based on outside knowledge, it was easier for them to think about how it could be applied to the product because they had an object to demonstrate its relationship.

4.2.3 IDENTIFYING NEW GROUNDS FOR IDEATION

Although the 3D printed pieces were not a hundred percent functional, problems which before were not previously considered started to appear. For example, the prototype was much smaller compared to the past product which made apparent some ergonomic issues (i.e., missing handle for proper holding). The experience also helped identify challenges that were not even conceptualized at the beginning of the project, in the first phase of the workshop or even prior to it. For example, through interaction with the 3D printed objects, the scientist suddenly realized that a source of light could be added to the design to make the experiment more effective. This idea was not initially conceived during the first phase of the workshop. The new idea was a result of physically comparing and contrasting the different prototypes which sparked a hidden need not previously addressed. Handling the prototypes and comparing their initial ideas to what had become physical allowed the participants to specify what they initially meant and made it easy to clarify obvious and not so obvious solution paths for the design. The ability of participants to identify hidden needs that would ultimately impact the design allowed them to ideate on different, new and refined solutions. While the participants struggled with moving away from their initial ideas and focused most of their time on the refinement of their initial idea, they effectively co-created alternative solutions with additional benefits. Participants expressed during their follow-up interview that they felt that the ideas they generated during the second phase of the workshop could not have been conceived without the help of the 3D printed objects.

4.3. THE POWER OF COLLABORATION

In this section, two examples will be presented from the researcher's previous experience working with the neurobiology laboratory in which the 3D printer alongside co-design practices was used to develop customized laboratory equipment.

4.3.1. MATING DURATION ASSAY

Purpose

In the first example, scientists in the Ottawa U. Neurobiology Department identified the need for the neurobiology laboratory to come up with a new product which would help measure fruit-fly mating behavior. Previously the lab was using a laser cut chamber which was lacking usability and functional aspects. There was a consensus that the product was not reliable due to the potential for human mistakes and the impossibility of focusing on the behavior of dozens of flies at the same time. Other problems, such as handling the specimen were also showing to be problematic. The general agreement was that a fruit fly specific chamber needed to be designed so that the management of the specimen would be easier. In addition, the chamber would have to hold more flies and would offer a user-friendly product use cycle.

The purpose of the design process was to develop a customized product specific for the study of the mating behavior of the fruit fly in a more efficient way. The project was initiated by the neurobiology lab with the hopes of generating a new tool that would optimize data gathering at the same time, this data would become more reliable by excluding human mistakes. The project followed an optimization path of their current manual non-specific fruit fly mating behavioral tools. This project evolved into a computer-based system that would record the flies automatically using the designed chamber and data would then be processed by machine learning technology. This newly designed equipment would allow enhanced capabilities to gather data from the mating behavior of the fruit fly, thus freeing an immense amount of time that technicians spend when using non-specific equipment to do the job. It was later in the design process that the idea of automation and machine learning would be introduced as a second phase of the project and as a result of the unexpected rapid optimization of the tool.

Workshop Design

It was decided that the technicians, neurobiologists, and designer would, through co-design sessions, take part in the design process of the tools that were going to be used by them. Although non-fruit-fly specific tools and attempts at 3D printed artifact were previously used to address the challenges identified by participants, none of them completely satisfied the laboratory's needs. Nonetheless, these designs were taken into consideration as a basis to design

For the co-design process, it was important for the participants involved to establish a common understanding of the goals of the process, the status of the existing products, the ideas and design iteration being developed throughout the process and the role of prototyping in the overall design process. The availability of participants was determined to establish a timeline where ideation and simulation practices, as well as 3D prototyping and 3D modeling, would be performed. Sequence and timing of these phases were important to prevent rushing into solutions without ideating a diverse range of alternatives.

The participants were made aware that the design development would take between 7 to 10 weeks to be completed and at least seven sessions of 1 hour each would be required. They were also informed of the activities that would take place and reminded that this co-design experience would rely on their participation rather than on individual intervention by the designer. The main purpose of the co-design activities was to jointly generate ideas to solve their identified challenge. These ideas would later be processed in a backstage phase of 3D modeling and printing carried out by the designer, allowing the participants to visualize their ideas in a physical state in the next session.

The co-design sessions were conducted twice a week. Although both sessions took place in the laboratory, the activities performed on each differed greatly. The first session of the week was a collaborative experience where the non-designers and designers participated in different ideation activities (brainstorming, post-it notes, sketching) to generate ideas that would be translated into prototypes. The second session of the week focused on simulating work-like settings by participating in simulations using the prototypes generated in-between sessions. This allowed the expertise and insight of the participants to be developed in a practical manner and enabled the ability to easily identify whenever there was a clear failure or breakdown on the prototype or a new idea triggered by the interaction and discussion around it.

The backstage phase of the co-design sessions when the 3D model was digitized and printed required design experience in order to translate the ideas and information from the non-designers into a printable object that reflected the needs of the participants. Although modifications to the 3D file could have been done on the spot in the sessions, this would have taken considerable time because of the range of ideas being generated at the moment. Instead, after every session, there was a modeling period in which the design would be updated, iterated or even completely remodeled through CAD tools later to be 3D printed.

Sessions

During the first week of these sessions, a team of five participants joined into a single group. Three of them were technicians, one was the head neurologist and the other the designer. From the group, only the head neurologist and two of the technicians were familiar with each other, and the fruit fly research. At the beginning of the week, all participants were required to attend an informative, technical meeting in order to understand the nature of the studies being performed in the laboratory. Everyone listened to a 45-minute presentation about basic information of the fruit-fly, the main direction of the scientific study and how understanding its behavior would benefit the scientific community by helping understand basic behavior concepts related to the genetic modification of the specimen. Observations, notes, and comments were written down by each participant individually, excluding the head neurobiologist who was already familiar with the subject. These notes included questions from participants such as: how long does the specimen live? How to recognize male and female flies? How to manage the specimens? What extra instruments are usually used? The neurobiologist provided the group with explicit feedback and complete explanations of how they handled this specimen, as well as information on the natural boundaries for the fruit fly life-span, such as temperature required and dietary regime.

The first session focused on understanding the technical scope of the scientific research and framing the problem with specific information on how to maintain the fruit-fly in the best conditions in order to document its' behavior. Technicians and scientists understood the limitation much easier than the designer who had initial concerns about the specific details which were foreign to his profession.

During the next workshop sessions, the reflective exercises were mostly based on the observations of the technicians' experience working with the previous chambers and the expertise of the neurology of fruit fly conditions to further complement the observations and ideate new solutions.

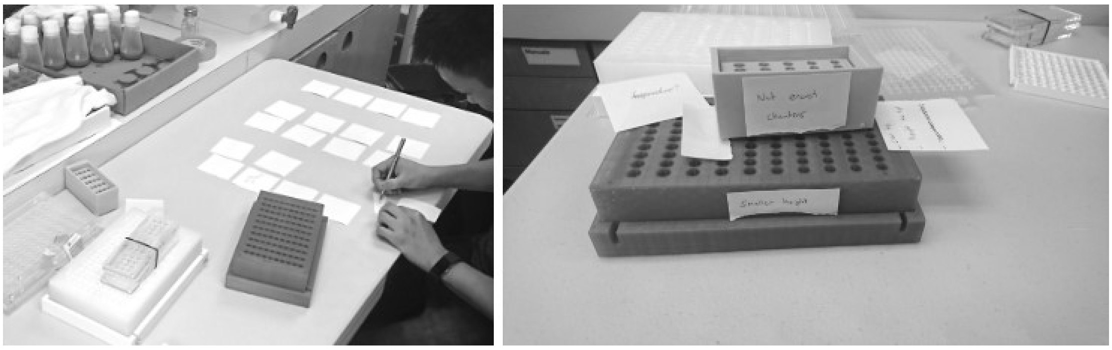

Figure XVIII. (left). Scientist gathers and categorizes his ideas from previously used prototypes. (right). Old prototype pile with usability and functionality comments

It was important to combine the previously used prototypes with additional idea generation techniques, such as brainstorming, to allow the team to prevent the team from fixating on one prototype and allow other solutions to be generated.

As notes, observations and ideas started piling up throughout the workshops, the participants categorized this information into different themes such as solutions, challenges, observations, considerations, and limitations. This type of information coding helped the participants understand what aspects of the design would need more focus and what could be addressed at a different time of the process. It also helped the designer understand technical information related to the fruit fly behavior that needed to be reflected in the prototypes.

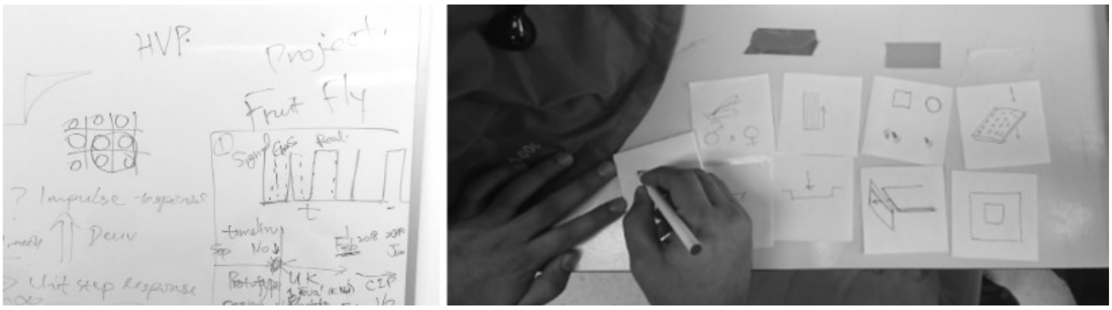

Figure XIX. (left). Initial explanation for mating behavior research logic. (right). Lab technician tries to imagine in sketch their ideas for mating behavior assay.

As expected, not every idea the group came up with during the session was useful or relevant- some of the prototype ideas simply focused on esthetic aspects, ideas that required filtering in or out further into the design process. For example, a couple of times the group wanted to choose the more simple solution that would not require complex manufacture, but they were constantly reminded that thanks to the 3D printer, manufacture would not be an issue and that they could let their imaginations run without worrying about manufacturability.

After initial ideation practices took place, a 3D printing period took place where revisions to the 3D models were made with the suggestions gathered in previous sessions, and a new version of the product prototypes was generated. Different CAD software was used at this point, sometimes, the ideas collected would be easier to represent in organic modeling software such as blender or ZBrush, while other times, the observations and ideas generated by the participants revolved around slight dimension changes, which required a parametric form of 3D modeling and the use of software such as Solidworks or Fusion 360.

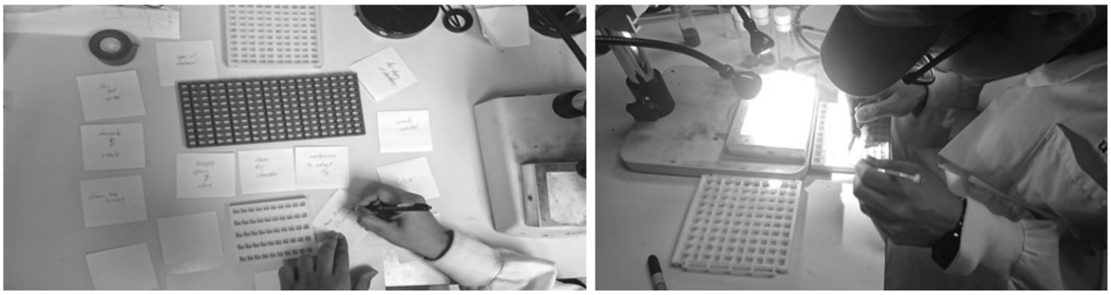

Figure XX. (left). Scientist categorizes some ideas generated from the first interaction with 3D printed ideas. (right) Scientist interacting (simulating his work) with the 3D printed objects resulted from the ideation practice.

Results of Sessions

Participants showed a high level of engagement and excitement to see their ideas becoming physical assets. As a result, participants' discussion focused on possible scenarios and further development that could be done in the project. Overall, the participants were more vocal about their opinions and ideas and would find it easier to jump into the discussion while grabbing the prototypes. Prototyping became an essential part of the design process by helping uncover hidden needs from the user, the process of interaction with the prototype helped the non-designer contribute to the design process and by doing so, improve the product. The engagement in simulation experience resulted in usability aspects being targeted by the scientists; the participants had moved on from functionality and were now focusing on the management and comfortability of the prototypes.

By the end of the tenth workshop session the team had learned from the process that by using the partially functional and fully functional high fidelity 3D printed prototypes, the participants were able to formulate their suggestions and ideas much better. It was not necessary to get everyone to understand the issues from pretending mock-ups or sketches because the physical object would relay this information directly. Also, it was not necessary to fit every suggestion into the prototypes as long as some solution could be found that made everybody comfortable with future use. This was most apparent from the human factor perspective, where some technicians would feel the prototype was lacking, others had opposite thoughts.

Figure XXI. (left) Participants of the co-design experience comparing the best 3D printed design idea candidates. (right) scientist pointing out defects on the product early prototype.

Other aspects of the design that were affecting the practice were identified by this point, such as the color of the plastic, which turned out to affect the flies vision and the camera perceived depth and shape of the chamber, which was affecting the flies behavior and user-friendliness of the device.

On the final session of the co-design experience, participants were asked to rank the prototypes according to those that best met their needs and addressed the challenges identified. The two best design idea candidates and the newly most up-to-date prototype were used as a centerpiece for the final session's activity.

Each participant was provided with a pen, and as asked to list the benefits of each of the prototypes in post-it notes surrounding such prototype, by this point most of the participants had extensive experience in using the prototypes and pointed out good or bad factors which seemed to come naturally to them. Where some prototypes were lacking, the next one would compensate and it was easy for the participants to see the evolution the prototype had taken over the course of the sessions.

The designer took notes and discussed with the group the nature of the comments. Most of the comments gathered through this activity pointed out the material quality and smoothness, which influenced the use cycle of their activity. For example, washing the chambers would become difficult because of the “ribs” created by the resolution of the print. This was an aspect that could be easily taken care of by using different print settings.

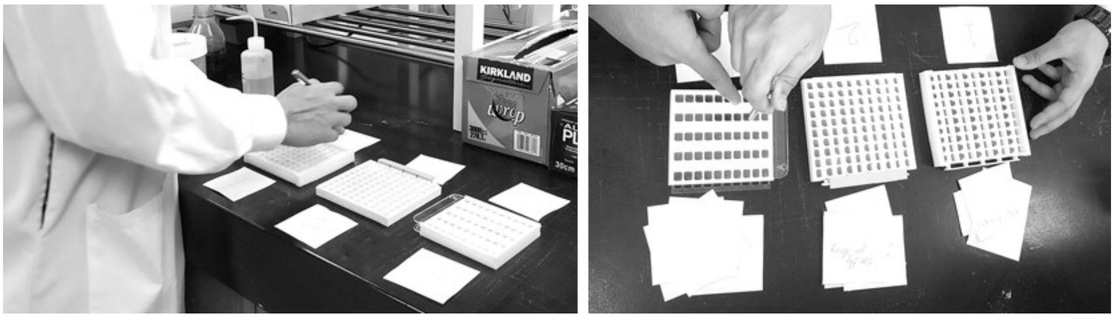

Figure XXII. Participants use post-it notes to organize their ideas and rank the prototypes.

The workshop sessions ended after discussing which early prototype would solve the problem better. Although slight modifications were required, this concluded the design process of the fruit fly mating behavior chamber. The next step was to introduce the machine learning aspect, a process which continues to be developed through a co-design experience as of today. Overall, all participants were able to communicate their concerns regardless of the level of experience accumulated through the co-design sessions, novice technicians could easily see and identify the different factors that made the prototypes different. Identifying functional or dysfunctional characteristics through targeted ideation came in the form of natural exercises when interacting directly with the early prototypes. Ultimate concerns would focus on the quality of the plastic and durability of the equipment, which suggested the need for using a higher quality for reproducing the equipment tool designed.

4.3.2. FEEDING BEHAVIOR ASSAY

Similar to the previous example, the second project followed a collaborative approach using the 3D printer to develop a feeding behavior assay. Initial ideas were collected and harvested from the participants in order to represent them in 3D form through the use of the 3D printer. Additional ideation practices took place in order to continuously evolve the design of the customized product by allowing the participants and specimen to interact and engage with the 3D printed prototypes.

In this project, scientists, as well as electrical engineers, took part in the design process. The 3D printer was used to address both scientific and engineering needs and requests to fit the adequate components required for the proper use of the product. In the initial stages of this project, ideas generated focused on the fruit-flies well-being and how the product should not interfere with its natural behaviors. The use of 3D printer was exceptionally useful when representing the iterative ideation process of the participants and to confirm or simulate semi-functional prototypes.

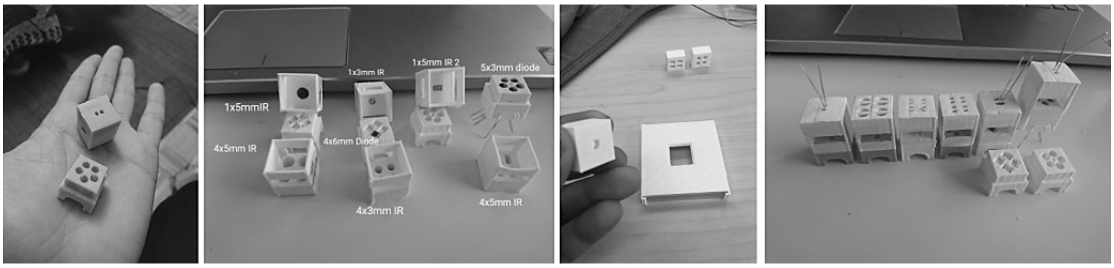

Figure XXIII. Initial ideas from engineers and scientists 3D printed for first ideation workshops.

The same ideation process using co-design practices took place to focus on the fruit-fly aspect, the engineering point of view (electronics and sensors to measure fruit fly activity) and the scientist perspective of using the device. Parallel to the electrical engineering point of view, and the scientist perspective on use and functionality, the design would be supported by the industrial design.

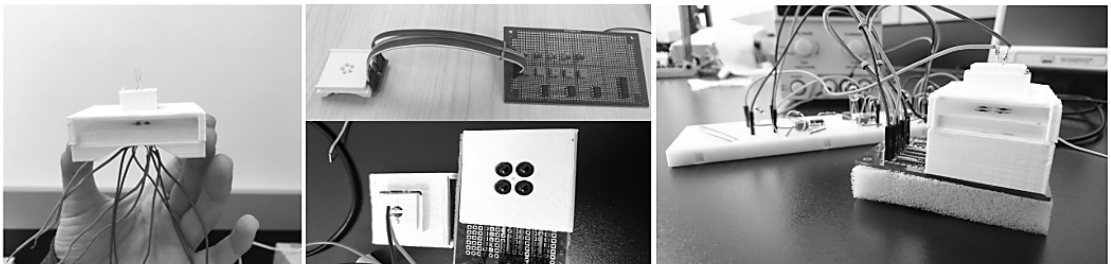

Figure XXIV. Design iterations are tested for electrical engineering functionality as well as for properly housing the fruit-fly specimens.

The project evolved throughout co-design workshops that included both scientists and engineers interacting and engaging in ideation practices through the use of traditional tools (i.e. paper, pens post-it notes), and reflecting on 3D printed prototypes of the ideas generated through these sessions. This resulted in a fully developed product to measure fruit-fly feeding behavior which the team called flyFAT (fruit fly feeding automation technique).

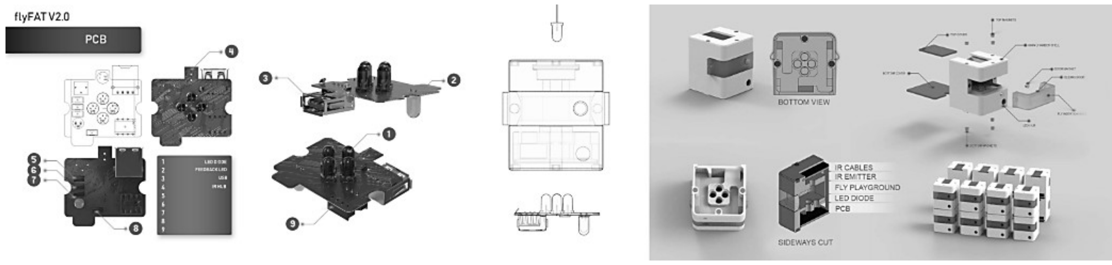

Figure XXV. Design iteration resulted from ideation workshop sessions represented by the Industrial Designer.

An updated version of this project can be seen in the following link: (https://youtu.be/QPLk3dxTlw0). This project is another example of the application of the 3D printer to enhance the design process and its power of collaboration and the potential benefits of using 3D printing to enhance the scientist and non-designers ideation process in co-design practices.

5. CHAPTER IV – CONCLUSION

In the field of design, increasing attention has been placed on including the end user in the design process to ensure products developed meet their specific needs and benefit from their domain-specific knowledge through Co-design. As discussed, a major challenge in incorporating the end user in this process is that they often do not have design experience and therefore approach creativity and idea generation from a different perspective and way of thinking. This is particularly evident in a lab environment where multiple disciplines (i.e., engineers, technicians, and science researchers) need to benefit from the tools used but have difficulty expressing their ideas in design vernacular. Co-design tools can aid scientists in expressing their ideas and thinking more “outside the box.”

The majority of literature on Co-design tools has focused on the benefits of basic 2D tools (i.e., office supplies) and low fidelity prototypes in spurring idea generation. What is missing from the literature is the potential impact of 3D printing on idea generation and creativity. 3D printing has had a revolutionary impact on the design field and has been used in the context of the science field to develop prototypes and products. The literature on 3D printing in design tends to focus on its manufacturing benefits rather than its potential during the ideation phase of design and impact on communication between Co-design participants.

This gap in the literature led to the paper’s research question to explore how 3D printers can facilitate the process of mutual communication and collective idea generation between scientists and designers in order to aid in the generation of new or refined ideas and uncover hidden needs to further the design process. It was argued that the low-end spectrum of 3D printers could enhance the collective ideation process of scientists by enabling creative play and simulation with physical representations of their initial ideas.

To answer this research question and test the hypothesis, a case study workshop with scientists was organized to probe their ideation process with 3D printed objects and gain insights on the influence of 3D printed objects in the individual and collective idea generation process. The workshop experience demonstrated the potential for 3D printed objects to positively impact the ideation process, especially in multidisciplinary Co-design environments. More specifically, the objects provided a shared medium for participants to explore their ideas and enabled them to make more informed choices towards what design ideas should or could be implemented. Furthermore, participants' engagement levels were drastically boosted when presented with representations of their own ideas, creating a sense of ownership over the project.

A main finding of the workshop is that the 3D printed objects allowed the participants to imagine future scenarios while providing a comprehensive context for reasoning. This allowed them to simultaneously explore ideas "outside of the box" and bring back those ideas into a realistic plane. This experience allowed participants to demonstrate alternate problem-solving strategies by enabling full ideation cycles in short periods of time. Furthermore, by allowing participants to visualize and identify new challenges in the design, the 3D printed objects allowed participants to imagine the future of the product and design. For example, participants were able to imagine potential opportunities for automation and introduction of machine learning with the project. In addition, the participants' diverse interaction with the 3D printed objects enabled focused theme dialogue and discussions allowing them to concentrate on generating ideation opportunities which led to ideas that would not have been created otherwise— an observation confirmed by the interviews with the participants. Finally, there was a clear difference in the motivation levels of engaging in the design process displayed by the participants between Phase I and Phase II. This can be attributed to the 3D printer which enabled interactions between participants and resulted in a richer brainstorming and ideation session. It also demonstrated and confirmed that 3D printers could help create an environment of mutual learning, enabled by the interactions between the participants and the 3D printed early idea concepts. The mutual learning experience allowed the participants to engage in a much more intense and focused conversation, diversifying their ideas based on the perspective of each participants' type of use with the objects. In general, the clearest impact of the 3D printed objects on the scientist's ideation ability was attributed to the richness of their interactions and playful experiences with the 3D printed objects.

Although the scope of this study was very narrow, the workshop demonstrated that the cognitive aspect of generating ideas is directly influenced by the adoption of physical models or early prototypes for this particular group and project. The workshop also hinted at the importance of selecting the most appropriate tool for ideation when engaging with the participants in order to trigger their creativity.

The hypothesis requires further exploration through additional tests to demonstrate its validity in other Co-design environments outside the lab context. Widening the breadth of the sample and offering more workshop ideation examples would aid in providing additional credibility to the claim that 3D printers have a direct impact on the ideation process of scientists, enhancing their abilities to communicate and generate ideas in Co-design contexts. To further identify the benefits of the 3D printer in the ideation process, special attention should be casted to the type of interaction it can spark. This may result in concrete guidelines and techniques to guide the designer towards the best choice between multiple strategies when using the 3D printer to enhance the ideation practices of non-designers of scientists. In addition, further research on better understanding the diverse interactions enabled by the 3D printed objects might shed light on different ideation themes. Given the continuous evolution of additive manufacture technologies and its increased use in the science field, identifying proper and preferred methods for ideating with the aid of 3D printers could be fundamental for drafting comprehensive methods, tools and technique to foster the multidisciplinary relationship of design and science. Future research should focus on probing and exploring how this technology can influence the creative process since 3D printing is rapidly spreading in both industries and academia, but the effect of designing with 3D printers on parameters like ideation, creativity and how to avoid design fixation is not apparent.

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APPENDICES

APPENDIX A: ANALYSIS OF INTERVIEW FEEDBACK

	Experience with working with 3D printing	Preferred method of communication	Type of interaction with the 3D printed objects	Main benefit identified from introducing 3D printed objects into their problem-solving strategy	3D printed objects impact on the design process
Engineer	No experience, but familiar with the concept	Sketching, doodling	Testing and verifying, comparing thoughts with prototypes.	Considers that the new limits of 3D printing allow expanding your mindset to imagine what is possible to create	Capabilities of the 3D printer helped to expand his thoughts on what is possible to create.
Scientist	No experience and not familiar	Discussion and brainstorming	Trial and error, testing identified problem with best options.	Recognized how the 3D printed objects allow him to stop depending on other researchers work and focus on generating his own ideas	Changed approach to developing designs by relying on his own ideas rather than other people's work.
Technician	No experience and not familiar	Discussion and brainstorming	Simultaneous Play and simulation of the experiment.	The great results given in the short period of time invested	It allows him to foresee problems and generate multiple solutions.
Designer	Experience working and designing, very familiar	Sketching, mind-mapping, Prototyping	Observation	N/A	N/A

APPENDIX B: INTERVIEW PROTOTCOL

Interview Protocol: 3D printed prototypes to facilitate an ideation process in an Interdisciplinary design context.

The purpose of this interview is to gather your insights on your experience working with the 3D printed parts during the facilitated interactive session with the researcher.

We would like to understand how your engagement with the 3D printed parts helped generate ideas for the design process. The information collected during these sessions will be included in my masters research paper.

The interview will take 30 minutes and with your consent interviews will be audio-recorded. You may still participate in the session if you choose not to be audio recorded. These recordings would be stored on an encrypted and password protected USB which will be kept in a locked cabinet at Carleton University. The recording will only be used by the researcher for analysis and will be destroyed once it has been transcribed and analyzed. All responses will be kept anonymous and your name will be removed from the data.

Please complete the consent form prior to participation.

QUESTIONS

1. Prior to this workshop session, did you have any experience designing with the aid of 3D printed objects? If yes, can you describe how the 3D printed pieces were used? What about prior to the workshop?

2. Prior to the introduction of the 3D printer (first session), did you have any challenges communicating and/or generating ideas in a multidisciplinary setting? Please provide examples, where possible.

3. Once the 3D printer was introduced into the design process, can you please describe what you did with the 3D printed parts?

4. In your opinion, did the use of the 3D printer aid you in communicating your ideas in a multidisciplinary setting? Please explain and provide examples where possible.

5. In your opinion, did the use of the 3D printer aid you in developing new or better-refined ideas during the design process? Please explain and provide examples where possible.

6. Can you describe the process you generally follow when developing a solution to a problem? Did the introduction of the 3D printed parts change your typical approach? Please explain.

7. Do you think the same ideas generated today (workshop) could have been developed without the use of 3D printed parts?

APPENDIX C: CONSENT FORM

CUREB-B Clearance # 110520

Consent Form for study entitled: 3D printed prototypes to facilitate an ideation process in an Interdisciplinary design context.

I ______________________________________, choose to participate in a study of the ideation practice while using 3D printed prototypes. This study aims to explore how 3D printed prototypes can facilitate the ideation process in an interdisciplinary design context. The researcher for this study is Pablo Arzate from the School of Industrial Design under the supervision of Prof. WonJoon Chung. This study involves two stages, the first phase is the initial ideation discussion where the design challenge will be identified, it will take place in room 3157 of the Department of Cellular and Molecular Medicine in the University of Ottawa.
A 3D prototype concept model will be developed by the designer after the first session based on the insights of the first meeting, they will be provided at the beginning of the second phase. The second phase, which will take part 2 days after phase one, will consist of the observation of the design team's group ideation process when using the 3D printed prototypes provided, followed by individual private interviews. During the interview, we will ask you a few questions about your experiences to gain some insight on the role of the 3D printed parts in the idea creation process.

First phase of the workshop will require a time commitment of 45 min, the second phase of the workshop will require a time commitment of 1:30 hrs., including the 30 min interview.

With your consent, workshop and interviews will be audio-recorded and photographed, though, you may still participate in the session if you choose not to be photographed. These recordings would be stored on password protected USB which will be kept in a locked cabinet at Carleton University. The recording will only be used by the researcher for analysis and will be destroyed once it has been transcribed and analyzed. All responses will be kept anonymous and your name will be removed from the data.

You have the right to end your participation in the study at any time during the session or up to a month after the session. You can do this by communicating with the researcher your desire to withdraw. If you withdraw from the study, all the information you have provided will be immediately destroyed. All responses to the interview questions are optional. If you do not wish to answer a question, or are uncomfortable talking about a topic just let the researcher know

If you decide to participate, you will get a free gift card with a value of $10 to be used in a popular café (i.e Starbucks, Tim Hortons). If your decision is to withdraw from the study early for any reason, you will still be compensated with a gift card with half of the value.

The ethics protocol for this project was reviewed by the Carleton University Research Ethics Board, which provided clearance to carry out the research. Should you have any **ethical concerns** with the study, please contact Dr. Bernadette Campbell, Chair, Carleton University Research Ethics Board-B (by phone: 613-520-2600 ext. 4085 or by email: ethics@carleton.ca). For all other questions about the study, please contact the researcher researcher Pablo Arzate at pabloarzate@cmail.carleton.ca or the thesis supervisor WonJoon Chung at wonjoonchung@cunet.carleton.ca

Do you agree to be audio-recorded: Yes ___No __

Signature of participant: ___________________________

Date: _______________________

APPENDIX D: VERBAL RECRUITMENT SCRIPT

VERBAL RECRUITMENT SCRIPT

My name is Pablo A, a graduate student from the Department of Engineering and Industrial Design at Carleton University. I would like to invite you to participate in my research study to explore how 3D Printed Prototypes can Facilitate An Ideation Process In An Interdisciplinary Design Context.. You may participate if you are a university student from any discipline (i.e. Engineering, Computer science, Biology) who have worked in developing products, tools, and assays to assist the department of molecular medicine in their scientific fruit-fly related research. Please do not participate if you are an undergrad student or do not meet the participation criteria.

As a participant, you will be asked to participate in two small ideation workshops The first phase of the workshop will require a time commitment of 45 min and will consist of discussion and simple ideation exercises, the second phase of the workshop will require a time commitment of 1:30 hrs, including the 30 min interview and will consist of interacting with 3D printed prototypes and further ideation practices. During both phases, audio and photo recording will be used to gather information, you may choose not to be photographed or recorded by letting the researcher know.

If you chose to participate you will be compensated with a 10$ gift card for a popular coffee shop. In addition, any personal data gathered throughout the workshop will be stored in a password protected USB at Carleton University. This information will be anonymous and you can request to destroy it within one month of your participation.

If you would like to participate in this research study, you can contact me personally through my email (pabloarzate@cmail.carleton.ca) or directly call my phone number (343)882-84-04.

Do you have any questions now? If you have questions later, please contact me through email or phone. You may also contact my supervisor, Prof. WonJoon Chung, at wonjoonchung@cunet.carleton.ca.

APPENDIX E: INTERACTIVE WORKSHOP SHORT DESCRIPTION

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Interactive design sessions and observations

Phase I - Initial discussion on design problem

Participants will be asked to identify from their perspective the main challenge of their product design. They'll be asked to develop ideas using traditional methods of communicating design such as sketching, dialogue, and post it notes.

Phase II - 3D printed objects are introduced

The designer will take the ideas generated during phase I and develop a 3D printed representation. This 3D printed object will be provided to participants and they will be asked to engage on a second round of idea generation.

Observation collection

Throughout the design process in phase I and II, the researcher will collect detailed notes on the way participants engage in the idea generation and creative process. Observations will be complemented with existing literature on the topic and feed into the methodology for the final paper.