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SHAPORATOR: ENABLING DESIGN ITERATION FOR YOUNG DESIGNERS THROUGH SHAPE VERBALIZATION

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ABSTRACT

We investigate speech-based input as a means to enable reflective thinking for younger individuals (middle - and high-school students) during design iterations. Verbalization offers a unique way to externalize ideas in early design and could therefore lead to new pathways for exploration and iteration, especially for K-12 students who possess the creative potential but are not technically trained in the design process. Interactive design systems, however, by-and-large utilize sketching, multi-touch, and gestural inputs. As a result, (1) there is little know-how regarding how to operationalize verbal inputs as a meaningful way to facilitate idea exploration and (2) there is little fundamental understanding of the underlying cognitive mechanisms for iteration through verbal communication. We take the initial steps towards these gaps by first designing and implementing the ShapOrator interface that takes verbal descriptions of geometric parameters (shape, size, instances) in a semi-natural language form and determines the appropriate transformations to a given design artifact modeled as a shape assembly. Using ShapOrator as our experimental setup we conducted an in-depth observational study on 10 middle - and high-school students tasked with designing spaceships. Our study revealed that participants were able to create a variety of designs while associating functional and topical contexts to their spaceships throughout the design iteration process.

1 Introduction

1.1 Context & Motivation

Our goal in this work is to explore verbal descriptions as a means to support iterative idea generation for young individuals. Iteration plays a central role in the early design process [1], where the goal is seldom to come to a conclusive solution to a problem. Instead, one is trying to refine their understanding of the problem through repetitive experiments and reflecting on the outcomes,

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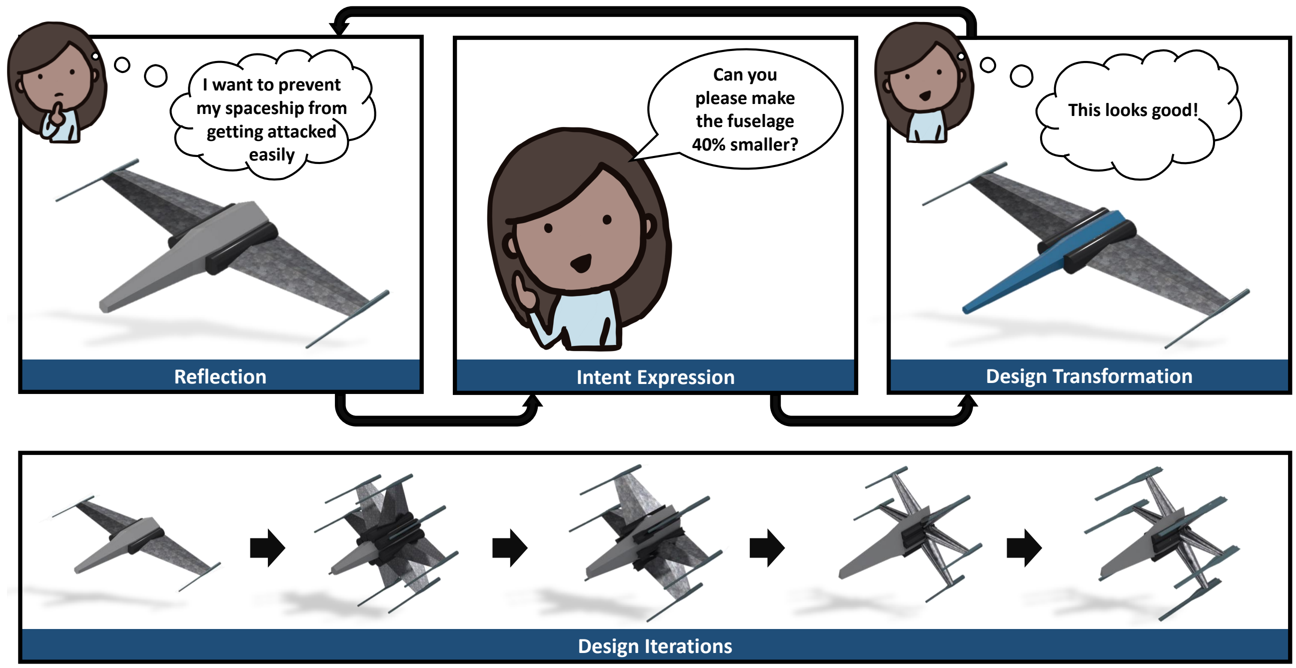

FIGURE 1. General overview of our *ShapOrator* workflow in action. (Top Row) User's cyclical design iteration process consists of three main phases: Reflection, Intent Expression and Design Transformation. The user reflects on their desired intents, verbally expresses their design intent to the *ShapOrator* system, which converts the verbal input into a visual design transformation. The specific design context here is that of spaceships. (Bottom Row) An example of the design iterations made by one of the users of our study. The user explored different shapes, sizes and instances of the spaceship.

thereby "*moving through the state space of possible designs*" [2]. As it is, providing meaningful computer-aided cognitive support for early design is a challenging task even for engineering students, given the divergent thinking involved in the quick exploration of a large quantity of ideas [3]. When considering younger students in the K-12 STEM (science-technology-engineering-mathematics) fields, the challenge increases even further. While these students may posses creative potential and design intuition, they do not necessarily have the formal understanding of the iterative nature of the design process. We specifically seek to investigate interactive methods for enabling design iteration for younger age groups.

Much of graphics and HCI literature on computer-support tools for design has, intentionally or unintentionally, adopted and embodied these principles of iteration and reflection. What is interesting is that the modality of "moving" (i.e. taking an action on the design) is almost always drawing with hands, as Schon imagines in his work [1]. There are numerous interactions, interfaces, and workflows that enable and/or study some form of design iteration through sketching [4–6], and even tangible and spatial interactions [7, 8]. Verbalization, on the other hand, has been little explored as a way to directly enable design iterations. This form of interaction might afford more convenience to the younger audiences [9] in the design process, and as such, we primarily focus on verbalization as an input modality to enable 3D design iteration in this work.

While verbal communication in design has been quite extensively studied [10–17], it is surprising that there is little known regarding how to utilize speech as an input modality in creativity support systems [18]. Even the systems that explore speech as an input for design modification tasks [19–21], either explicitly or in combination with other modalities, have not studied the fundamental cognitive workflow that verbal interactions enable in association to the design process. Our work is motivated by the observation that in order to enable iterative design through verbal communication, there is a need for fresh perspectives on how to enable speech-based workflows as well as systematic study of what verbal input affords in an iterative design process.

1.2 Background & Basis

Design iteration is an important part of the design process [22], where the designer goes through a series of steps and revisions to learn more information about their design problem and form a solution. The cognitive processes involved in design iteration are important to understand. Iterations can help in converting an ill-structured problem into a well-structured solution, which might not be obvious in the final design. Adams et al. [23], studied this by first identifying transition behavior as the behavior displayed by the designer while making decisions between the design steps, that can be in the form of information processing activities and decision activities. Next, they conducted a study, where they used verbal protocol data to observe how freshman and senior students introduced new information and knowledge into their design process, and categorised the data using their transition behavior codes. Using this approach, they were able to qualitatively and quantitatively observe the cognitive processes that occurred during the design iterations. Faste et al. [24], conducted a reflective study to understand the practice of intuition in design for an iterative aesthetic task. The users self-reflections regarding their iterations were documented over several weeks, where they observed four dimensions of intuition in design, namely efficiency, inspiration, curiosity and insight. Enabling design iterations, therefore, is a key requirement to allow users to gain important information and knowledge about the problem and generate solutions.

As such, interfaces that provide computational support to the design process, need to, at the very minimum enable and support design iteration [25]. Sketch-based interfaces have been widely studied and used to support design processes [26]. Zhao et al. [5], developed a framework 'skWiki', that supported collaborative editing of sketches, texts as well as photographs. Users had the ability to revisit not only their own but also their collaborators' past iterations and integrate it into their own designs. Similarly, Piya et al. [6], developed a sketch-based collaborative 3D modelling software where design iterations could be easily shared, and re-used between users, while being stored and accessed in a hierarchical form. Vinayak et al. [8], developed 'Mobisweep' to allow users to quickly generate iterations of 3D sweeps from sketches. While sketching as an interaction has been studied extensively, there have also been works that have used speech as an input to make design modifications. These works either form an extension to existing CAD softwares [20, 27] or use speech in multi-modal interfaces [19, 28]. They do not focus or document the exploratory and iterative nature of the design process.

The importance of verbalization during the formative years has been well studied and has shown to aide the process of learning and improving cognitive skills [9]. We learn through the process of verbalization even before having the ability to write or make sketches. In design, studies have shown the importance of verbal reflection in improving the design solution through the design iteration process [29]. The study by Bilda et al. [30] shows that the results that expert architects produced when verbalizing their ideas were similar to when they used sketching to communicate their ideas. Research in engineering design [31] has also shown evidence that while sketches are effective for communicating three-dimensional (3D) concepts, expressing the design intent to create those concepts is often more effectively initiated through verbalization, i.e. by using spoken language. While these works highlight the importance of verbalization in the design process, a deeper understanding of verbalization as an input modality to enable 3D design iteration is needed.

1.3 Challenges & Approach

As a first step towards understanding whether verbalization for design transformation is suitable for the design process, our objective is to first study whether such an interaction enables design iteration. There are three technical/technological challenges that emerge when considering verbal input. First, language is a highly contextual modality and interpreting user's intent even outside of design is quite challenging depending on the context. Second, verbal communication during the design process has been famously known to be ambiguous and messy [18, 32]. Finally, how we communicate in design is still not a well-understood. Wiegers et al. [11] classified different verbal patterns for describing how people talk about shapes. However, the way in which designers talk about functions and their relationships with shapes is currently not available to the best of our knowledge. Therefore, within the broader vision of multi-modal (vision, speech, sketch, gesture) conceptual design workflows, enabling a full-fledged natural language interaction is prohibitively challenging, if not entirely impossible. Toward this vision, we follow a constrained approach, where users are afforded semi-natural interaction as long as their design intents fall within a predefined vocabulary.

Inspired by Schon's cyclical ("*seeing-moving-seeing*") description of the design process [1], we formulate the design iteration process as a cyclic sequence of reflection, expression and transformation (Figure 1). Specifically, in our case, verbal input is central to all three activities. The user is reflecting on their past and future action by talking about the current design and expressing their intent verbally in terms of a specific design modification that should take place. We then envision an interactive workflow that interprets the verbal expression to effect a design modification on the fly. As a specific embodiment of our envisioned workflow, we implemented an example interactive system, *ShapOrator*, that takes users' verbal inputs and transforms them into 3D shape modifications. Note that the purpose of our implementation is **not to create a feature-rich system as such, but rather to enable the study of the reflection-expression-modification cycle**. Starting from a seed design template, users can change shapes, sizes and also the number of certain parts present in the template.

Using *ShapOrator* as an experimental workflow, we conducted a study wherein we invited middle- and high-school students with understanding of basic STEM concepts but no formal engineering or design coursework. The students were given the task of designing spaceships under the *'Star Wars'* theme. The task was open-ended and the students were free to make any number of designs within a given time-frame. In addition to the participants verbally expressing their design intents, we take inspiration from prior works [29, 33] and use elements of participatory design to extract verbal reflections on their design transformations during the course of the study.

Our study showed that the participants were able to explore a wide variety of spaceship designs using *ShapOrator*. Furthermore, we explicitly highlighted users' design iteration process through their reflective descriptions of their spaceship designs. We specifically showed the information and knowledge that users associated with their designs, in the form of functional & topical contexts, and how it motivated them to make further design iterations.

2 ShapOrator: Workflow & Interface

The main objectives for the design of our workflow were to study and enable the design iteration process constituting of - reflection, intent expression and design transformation. In order to study reflection, we incorporated aspects of participatory design to extract verbal reflection from users. We then developed an experimental interactive system, *ShapOrator*, to enable users' to express their design intent and visualize the design transformations.

The key considerations for the design of the interactive system included: (a) the design context given to the users which, in our case, was meant to engage young individuals; (b) the process of converting verbally expressed intents into machine-understandable commands; and finally (c) converting the machine-understandable commands into 3D design transformations, providing users a visual representation of their expressed intents. We expand on each of these design considerations below.

2.1 Design Context

Context plays a key role in the design process, as it motivates the users to make specific contextual design decisions. The users, in our case, were high school students taking part in an engineering summer camp. To observe interesting interactions and an involved design process, our context needed to be engaging and easy to work with. Taking inspiration from prior works, spaceships were used as our design context, as they had similarly been used for interactive activities involving children [34,35]. We specifically used the *'Star Wars'* theme to provide further context to the users. Spaceships provided a good balance between the complexity and possible variety of designs that the users could make. To enable further modifications, the users could change specific components of the spaceship, namely, the fuselage (also referred to as the body), wings, engines and missiles, thus, allowing them to explore more unique designs.

2.2 Intent Expression

Once the users had familiarized themselves with the context, their next step was to verbally express their design intents to the system. Our system took the users' verbalized input and converted it into machine-understandable algebraic descriptions to make the desired design transformations. Therefore, understanding and semantically decomposing the design intent played an integral role in accurately representing the design transformations. Xue et al. [20], accomplished this by describing a verb-based CAD semantic search, where they searched for verb phrases (verbs and objects) and complements (parameters) in a command. Similarly,

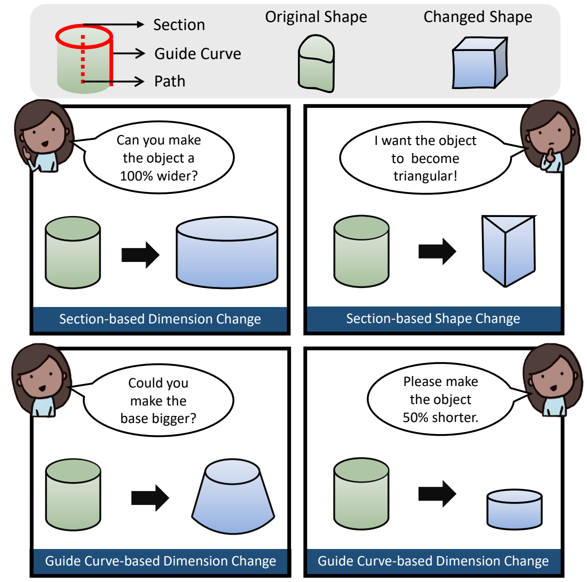

FIGURE 2. Different part-based changes that can be made using *ShapOrator*. (Top Gray Row) Curve components of 3D shapes include: section, path and guide curves. The original shape is shown in green and modified shape in blue. (Top Two Boxes) Two types of section-based changes can be made: dimensional changes (ability to make sections wider, narrower, taller or flatter) and shape changes. (Bottom Two Boxes) Guide-based dimensional change (ability to make radial changes: bigger/smaller; and length based changes: longer/shorter.)

Khan et al. [27], categorised words extracted from commands into object, dimensions, location, dimensional aspects and modifiers. Taking inspiration from these prior works, our first step was to understand what object the users' intents were referring to. In a multi-component design context like ours, we first searched the intent for specific components that the users wanted to change. The next step was to understand the type of transformation being requested for the identified components. Our system allowed three main types of transformations: cross-sectional shape changes, dimensional changes and adding/removing components to the object. Once the type of transformation was identified, we checked whether the users had mentioned any specifications corresponding to the transformation. For instance, the users could mention the amount of change they wanted to make, or add a number of components. This information was typically in numerical form and usually appeared before or after the desired transformation. Using this knowledge, we decomposed the user's design intents into meaningful hierarchical information that could conveniently be translated into machine-understandable commands.

2.3 Design Transformation

In order to facilitate the design transformation process using our system, we took inspiration from several prior works in com-

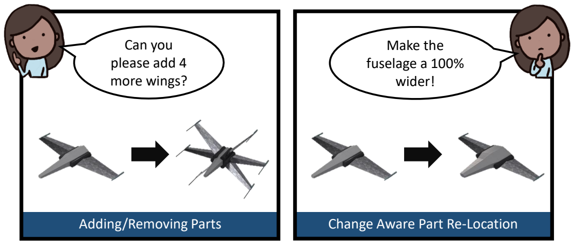

FIGURE 3. *ShapOrator* enables simple assembly-based changes. (Left Box) Ability to add and remove parts from the assembly. (Right Box) Change-aware relocation of parts in the assembly.

puter graphics that were based on component and assembly based modeling [36,37]. These systems typically started with a template design, where parameters were used to define each component of the shapes present in the template and a wide variety of designs could be created by simply changing these parameters. In our case, we closely followed the approach shown in [6] in terms of shape representation. Specifically, we considered the design of the spaceship to be a collection of swept volumes that were spatially configured to represent a spaceship itself. A fundamental reason for choosing swept volumes as our shape representations was that it gave an intuitive way in decomposing each individual surface direction of the shape into meaningful curve components, namely the section, path and guide curves (Figure. 2). While sweeps are popular in parametric modeling, they have a unique ability to allow intuitive design even for quick idea exploration, as has been shown by several works [8,38]. Therefore, we used speech as an input to make changes to parameters of swept volumes, allowing users to easily explore a variety of design transformations.

Here, we reiterate that the design considerations for our workflow were influenced by our desire to study how verbalization could be used to enable design iterations for young designers. Our goal, therefore, was not to developing a feature-rich software.

3 ShapOrator: Implementation Details

3.1 Software & Hardware Setup

Our user interface was developed using Unity scripted with the C# programming language. We used Azure's Speech SDK and Custom Speech API for our speech-to-text recognition module. Intent classification for text input was done using Azure's Language Understanding (LUIS) API. Our interface was deployed on an Asus ROG Zephyrus laptop with an AMD Ryzen 9 processor, 16GB DDR4 RAM, and NVIDIA GTX 3070 Laptop GPU. Built-in microphones were used to record voice.

3.2 Shape Representation & Modeling

Our shape modeling technique utilizes swept volumes to render the 3D parts of the spaceship. Sweeps enable us to easily explore a variety of different shapes by making changes to their sectional profiles and guide curves. Using this as the basis for our 3D modeling approach, we further discuss the shape manipulation functions present in *ShapOrator*.

3.2.1 Sectional Geometry Changing the cross sectional shapes of the sweeps, i.e., the 2D profiles of the sections, provides a quick and easy way to explore a wide variety of unique shapes (Figure. 2). In our approach, we utilize a parametric equation, specifically the superformula equation [39], to generate the sectional shapes. The superformula equation is a generalization of a superellipse and is able to generate a variety of shapes by simply changing its parameters as follows:

$$r(\phi) = \left(\left| \frac{\cos(\frac{m\phi}{4})}{a} \right|^{n_2} + \left| \frac{\sin(\frac{m\phi}{4})}{b} \right|^{n_3} \right)^{\frac{1}{n_1}}$$

Here, $x = r(\phi)\cos(\phi)$, $y = r(\phi)\sin(\phi)$, and the value of r corresponds to the radius of the superformula shape at angle $\phi \in [0, 2\pi]$, giving the polar coordinates of the superformula equation. Parameter m defines the number of corners of the shape, while parameter n_1 determines if these corners are sharp or flattened and also if the edges are straight or curved. Parameters n_2 and n_3 determine whether the shape is inscribed or circumscribed within a unit circle, i.e., when both a and b are equal to one. By keeping n_2 and n_3 equal to each other, we can obtain symmetric shapes. x and y form the Cartesian coordinates of the superformula.

We choose the superformula equation to generate our sectional shapes as it provides a convenient way of semantically mapping the shape descriptions to specific parameters corresponding to that shape. For instance, we can create a square by assigning the values of parameters m, n_1, n_2 and n_3 to 4, 1, 1 and 1. To create a 4-pointed star, we simply reduce the value of n_1 to 0.5 while keeping the other parameters the same.

In addition to the superformula-based transformations, we also added the ability to make the cross-sectional shapes smoother, i.e. make the corners of shapes rounded. We use Laplacian Smoothing using $\mathbf{p}_i = 0.5(\mathbf{p}_{i-1} + \mathbf{p}_{i+1})$ where $\mathbf{p}_i$ is the smoothed vertex for neighboring vertices $\mathbf{p}_{i-1}$ and $\mathbf{p}_{i-1}$. The smoothing is performed on the vertices corresponding to the x-y (horizontal) plane where the cross-sectional shape lies. In order to obtain a visibly smoother shape, the smoothing function is iterated 4 times.

3.2.2 Dimensional Changes In addition to allowing cross-sectional changes of shapes, we also added the ability to change the dimensions of the parts in multiple different ways. The users can change the dimensions of the cross-sectional shapes and also the dimensions of the entire parts which are defined by the guide curves of the sweeps (Figure. 2). The users can

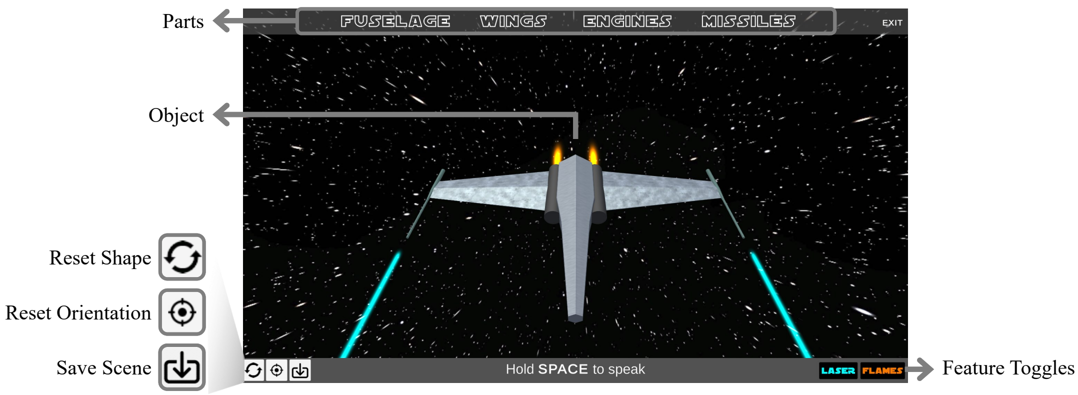

FIGURE 4. *ShapOrator*'s User Interface (UI) is shown. Users can modify different parts of the spaceship. To speak, users can hold down the space bar. Transcribed speech is visible on the bottom gray panel. The three buttons: reset shape, reset orientation and save scene are placed on bottom left corner.

make the cross-sectional shapes wider, narrower, taller and flatter. This is easily achieved by scaling the x and y coordinates as $x = s \times r(\phi)\cos(\phi)$ and $y = t \times r(\phi)\sin(\phi)$. Changing the values of s results in wider/narrower shapes, while changing the values of t results in taller/flatter shapes. The guide curves, on the other hand, help us define the outline of the different 3D parts of the spaceship, i.e. the fuselage (body), wings, engines and missiles. The control points of the guide curves help us define the specific features of the parts, such as the tapering shape of the wings or a cone like shape for the fuselage. The control points were initially decided through a trial-and-error approach taking inspiration from the spaceships in the Star Wars movies, specifically the X-Wing design. The guide curves, therefore, enable a convenient way to change the dimensions of the 3D parts by simply changing the positions of the control points. For instance, if the user wished to make the parts radially bigger or smaller, the control points of the parts would be moved away or towards the central axis of the shape, respectively. Increasing or decreasing the length of the parts, would subsequently result in the length between the control points to increase or decrease respectively.

3.2.3 Parts Positioning and Grouping

The default template of the spaceship consists of one fuselage and two wings containing one engine and one missile each. The fuselage being the central part of the spaceship, acts as the reference point for the positioning of the wings. The initial two wings are attached horizontally to the circumference of the fuselage. The engine is positioned at an offset from the beginning tip of the wing (end attached to fuselage) along the direction of the wing's axis, while the missile is placed at the end of the wing's tip. While the users don't have the ability to re-position these parts, their positions are recalculated after every change to maintain consistency throughout the modeling activity (Figure. 3). Users also have the ability to add or remove extra wings in pairs, with two being the minimum and eight being the maximum wings allowed. Each new wing comes with an engine and a missile and these can not be individually added or removed. While these functionalities could be added easily, the constraints help maintain simplicity of the design process.

3.3 Speech Recognition and Intent Classification

A major component of our modeling interface is the ability to understand and act upon the user's verbally conveyed design intents. Speech recognition plays a significant role in this component. While most basic speech-to-text services are able to transcribe simple spoken sentences, they usually don't perform well for application specific commands that aren't typically used in day-to-day life. For this reason, we used Microsoft Azure's Cognitive Speech Services SDK as it allowed us to train custom speech models that catered specifically to our application. To train these models, we first collected and manually transcribed audio samples from eight individuals of varying backgrounds. Audio samples included sentences and commands that users' would typically use while interacting with our application.

Our next step, was to understand and act on the users' design intents. For this we needed to classify the users' intents into different actions that our interface would perform. Recent advancements in Natural Language Processing (NLP) [40] have made it easier to train models that parse and make sense of user intent from textual data. For our application, we used Microsoft Azure's Language Understanding (LUIS) service, which enabled us to predict the overall meaning of the participants' commands and gather relevant information from it. Using LUIS' cloud service, we were able to train custom NLP models tailored to our use case. We were required to define *Intents*, that represent tasks or actions, and *Entities*, that extract specific information from the users utterances with the help of specific features (such as synonymous words). For our application, we defined four intents: changing cross-sectional shapes, changing dimensions, adding or removing parts and undo. In order to improve the prediction of these intents, we provided the model with additional features to train on. The features included a list of different ways the parts could be addressed, a list of different shape descriptions as well as a list of the different terms for adding or removing parts. The model was then provided with a wide variety of example utterances to train on in order to increase the accuracy. As the LUIS service is built on pre-trained models, the quantity of examples mattered less compared to the variety. While our application did not support a completely natural interaction, natural sentences could be used as long as the necessary keywords were present.

3.4 User Interface Elements

Our interface comprises of two main modes: tutorial mode (no data is logged), and the study mode. Once a mode is selected, the users can see the object (spaceship) to modify in the center of the screen (Figure 4). The users can easily change the orientation of the object by rotating and zooming in/out with the help of the mouse. The parts constituting the object are labeled on the panel at the top of the screen allowing for easy reference. The bottom panel displays the transcribed texts and consists of multiple buttons to the left and right end of the panel. To interact with the system through speech, users need to press and hold the space bar while speaking. The three buttons, starting from the left, are for resetting the shape to its default template, resetting the orientation to default, and saving the current object. Buttons on the right are to toggle on/off the lasers and flames. Having buttons and mouse-based interactions for non-essential functions allows the users to focus on the design task at hand.

4 Experiment Design

Our user study was conducted during a university-hosted summer camp for middle - and high-school students. The summer camp aimed at providing exposure to these students to various hands-on engineering concepts through interactive activities. Our research group hosted the students for two days with the goal of introducing them to the different processes of Engineering Design. The theme for this session was *Spaceships*, as seen in science-fictional movies. With this in mind, the activities setup for the first day covered design ideation and prototyping, while the second day covered a 3D modeling tutorial to create spaceships using SolidWorks. We conducted our study with individual students during the second half of the second day.

4.1 Participants

The participants of our study were middle - and high-school students taking part in the summer camp. 10 students, in the age group of 13 to 17 years, took part in the study (9 male, 1 female). They were studying in grades ranging from eight to eleven. The students did not have any formal coursework in engineering or design. However, seven out of the ten students had some basic experience in the past with 3D modeling tools such as Maya, Blender, SolidWorks, Autodesk Inventor and Fusion 360, which they had either used for school or personal projects.

4.2 Procedure & Data Collection

Each user study lasted between 30-40 minutes. The participants were provided with a pre-study questionnaire to elicit their past experiences with 3D modeling tools and their opinions on verbal communication during idea generation. Next, we gave them a detailed tour of our user interface (UI). The users were then asked to complete the following tasks:

1. **Practice:** Participants were given an elaborate tutorial of different speech-based interactions that they could use to explore and change the shapes of the spaceship. They were given 7 to 9 minutes to practice all the different available commands and to clarify any doubts they had regarding the interface. No data was logged during practice.
2. **Study Task:** The participants were given an open-ended task of exploring different spaceship designs by building upon the default template. They were asked to explore a variety of designs, however, no limit was set to allow a natural process of shape exploration. The participants were given the context of the *Star Wars* theme, but were not expected to create any specific designs. They were given 20 minutes for the task and were asked to save their designs whenever they felt that they had created a unique design of their liking.
3. **Reflective Conversation:** During the course of the study, participants were asked questions to make them reflect on their design choices and decisions [29] after every three to four major iterations. The questions mainly targeted the reasoning behind the design changes and their effect on the overall design of the spaceship. This helped us understand how participants added information and knowledge as they iterated through their designs.
4. **Post-study Questionnaire:** Participants were asked to complete a post-study questionnaire to evaluate the ease of use of our interface and its creativity support for the shape exploration tasks [41] and also included a study specific survey. They were also asked to provide general feedback regarding their experience.

We collected a variety of data for each study session with a participant: (a) screen recording of the interface, (b) audio recording during study, (c) time-stamped transcribed user commands (d) intent and entity information from the language model (LUIS), (e) 3D mesh of the spaceship, (f) screenshot of the interface when saved and (g) answers to the pre and post-study questionnaires.

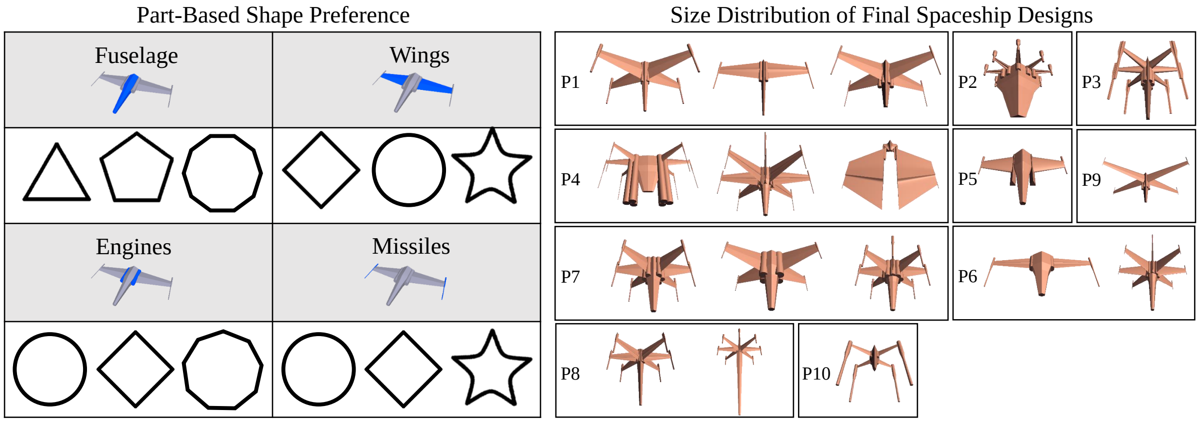

FIGURE 5. Preferred shapes for parts and their relative sizes in participants' final designs are shown. (Left Box) Top 3 most preferred shapes (ranked from left to right, left being the most preferred) for each part are shown. Participants preferred the triangular shaped fuselage the most, while for the wings, engines and missiles the top preferred shapes were the default shapes of the parts. (Right Box) The final designs of the spaceship that the participants made before trying a new design. Participants were free to decide the number of designs they wished to make.

5 Findings

We observed an overall positive user experience for the design task and the *ShapOrator* interface. The participants, in general, were able to explore a variety of spaceships by iterating through different designs. On an average, each participant made around 68 iterations to their spaceships (max: 111, min: 41). Any change that the participants made to the cross-sectional shapes, dimensions, adding/removing parts or undoing their design change, accounted for a single iteration. All participants preferred making the most iterations to the dimensions of the parts, followed by changes to sectional shapes. This may have been due to the extent of visual change corresponding to the functions. For instance, adding or removing wings made a significant visual change to the spaceship, while making the fuselage shorter by 20% didn't have the same effect. With respect to the changes made to specific parts of the spaceship, the fuselage was iterated through the most and missiles the least by majority of the participants (6 & 7 participants respectively). The reason for this could be the relative sizes of the parts and their relative importance in the spaceship.

Apart from the above quantitative results supporting the design iteration process, we wanted to develop a more fundamental understanding of the process from a qualitative point of view. To accomplish this we analyzed the users' reflective descriptions throughout their design process, that were verbally initiated by the study administrators' questions. We found that the users associated relevant information and contextual knowledge to their spaceship designs that motivated them to make specific changes. We categorized the reflections into two broad categories: functional contexts and topical contexts.

5.1 Functional Contexts

Functional contexts referred to the descriptions where the participants focused on the functional aspects of the spaceship to describe and justify their designs. Some example included the speed of the spaceship, how well it could fly, how well it could perform in a battle, how many people it could house, and so on. This led to the participants making iterative geometric decisions for modifying their spaceships to achieve their desired function. In the following sections, we highlight common functional contexts used by the participants in the form of their answers and interactions, and also through their geometric decisions such as the common shapes and sizes associated with specific functions. We note that some contexts naturally fell under multiple categories.

5.1.1 Aerodynamics

Aerodynamics was a common functional context that the participants focused on to create their spaceships. Three participants explicitly mentioned their desire to design more aerodynamic spaceships and attributed specific shapes and features of their designs to this function. When asked what design they were going for, P3 answered: "*A sleeker more aerodynamic look* ". Explaining further, they said: "*The rounder wings and the triangular [fuselage] and smoother engines, just in my head that's what contributes to aerodynamics. The sharper edges just don't look as aerodynamic*" (Row 1, Figure. 6). Similarly when P9 was asked for the reasons for their circular shaped wings, they answered: "*I guess the wind can pass through things that are circular more. I mean, yes, maybe angular would be better but in some instances it's better with a circular design.*", and for their triangular fuselage, they said: "*Well, a couple of things, I guess the wind passes through it a lot and it passes through pretty well and it has the smallest surface area on the end of it so it's the closest thing to a point, so I guess lesser the surface*

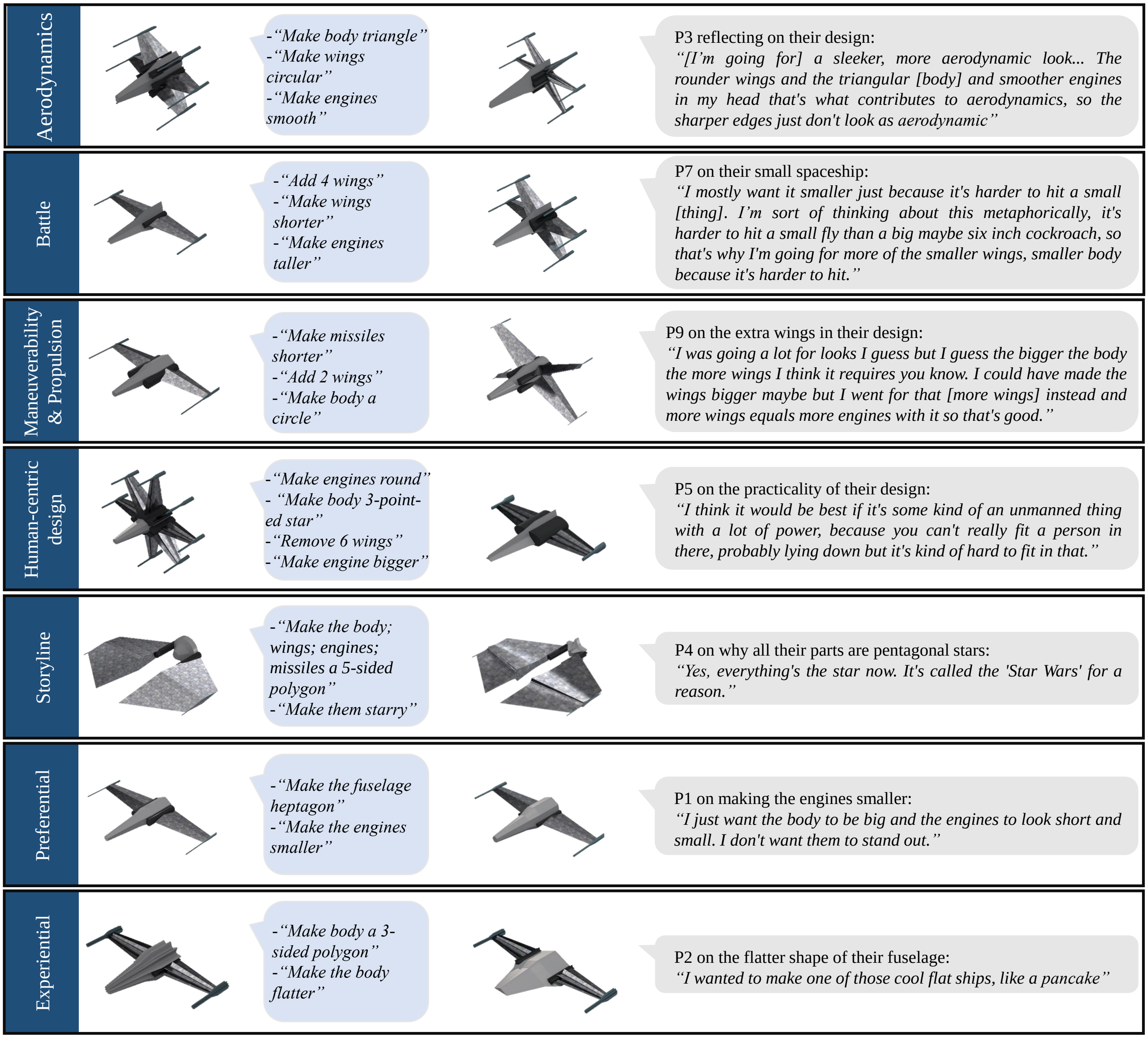

FIGURE 6. Examples of design transformations and their corresponding reflections made by participants between iterations. (First column, starting from the left) The examples are categorized based on the following contexts observed in the users’ reflections: aerodynamics, battle, maneuverability, human-centric design, storyline, preferential and experiential. (Second column) Designs picked before two to three major iterations leading to the design transformation (Fourth column). (Third column) Design intents that users expressed to make the design transformation. These intents are not the exact commands made by users and are only representative of the original commands. (Fourth column) Design transformations corresponding to the users intents. (Fifth column) Users’ reflections on the transformed designs.

area, the more aerodynamic it is, the faster it can move." The triangular fuselage was the most commonly used shape amongst the participants (Figure. 5). While some other participants did not mention the specific reason for the triangular shape, aerodynamics may have played a part in their decision.

5.1.2 Battle

The context of battle was a common theme in few of the participants' answers. The focus was divided between improving the defense of their spaceship and improving its attacking capability. However, there was no single approach taken by all the participants, and it led to a few unique design choices. When P10 was asked about the significance of the flat fuselage and large missiles in their spaceship, they said: "*It's hard to hit. It can just destroy everyone with the giant missiles* (Figure. 5). At a later iteration, P10 decided to make the wings much larger than the fuselage and said: "*Essentially, the cockpit cannot be shot because it is behind the wings.* This was an interesting approach since they made a part much larger to act as a shield for another part. In a similar approach of increasing one dimension but decreasing another, P8 mentioned: "*...The long and thin body makes it harder to hit I guess*. We also had participants take metaphorical approaches to make design decisions. One such instance was when P7 was asked if they were set on their cross-sectional shape preference, they answered: "*I'm mostly trying to change the shape right now to where it'll be overall smaller...I mostly want it smaller just because it's harder to hit a small [thing]. I'm just sort of thinking about this metaphorically, it's harder to hit a small fly than a big maybe six inch cockroach, so that's why I'm going for more of the smaller wings, smaller body because it's harder to hit*" (Row 2, Figure. 6). In total four participants associated their designs with the context of battle or war.

5.1.3 Maneuverability and Propulsion

We found that the contexts of maneuverability and propulsion motivated some participants to make dimension based changes and also played a role in the number of parts they added and removed from their spaceships. For instance, when P9 was asked for their reasoning for making a smaller spaceship, they said: "*I guess it's smaller and it's able to move better and the amount of engines it has probably moves extremely fast.*" On their second design, P9 said: "*Now I'm going for a more lightweight [design] i guess. I made the wings a little bit thinner*" and for their third design they added 2 more wings and when asked for a reason, they said: "*I was going a lot for looks I guess but I guess the bigger the body the more wings I think it requires you know. I could have made the wings bigger maybe but I went for that [more wings] instead and more wings equals more engines with it so that's good*" (Row 3, Figure. 6). We noticed that while participants added more wings to make their spaceships fly better, the increased number of engines also gave them incentive to add more wings. We noticed 2 other participants take a similar approach.

5.1.4 Human-centered approach

Participants in general did not take the human-centered approach for designing their spaceships and instead gave more priority to the visuals and other functions. However, when they were asked questions about the human-centered approach, they had interesting insights on how that aspect could be incorporated in their designs or how they could circumvent it completely by defining a new function for their spaceships. For instance, when P5 was asked about the practicality of their design, they answered: "*I think it would be best if it's some kind of an unmanned thing with a lot of power, because you can't really fit a person in there, probably lying down but it's kind of hard to fit in that*" (Row 4, Figure. 6). Some participants however, went with the dimension based explanation for incorporating the human-centered approach. To carry more people, P1 said: "*I would probably have it [fuselage] 30% larger*". P7 specifically designed a bigger fuselage to carry more people: "*Yes, it is now carrying like a team of two and I'm not sure if you watched Star Wars but in the fifth movie they're fighting on that ice planet and they have one person at the back for the gunner and one in front for the pilot and so that's kind of where I'm going with it now and I could probably even extend it to where it's a whole entire battalion even though it looks like an attack ship. I'm really just experimenting on how big it can get now*".

5.2 Topical Contexts

While functionality of the spaceship was an important factor in the participants' design iterations, they also used topic-based contexts to explore designs. We divide these topical contexts into Storyline, Experiential and Preferential. We give instances of participants using these to describe their design choices.

5.2.1 Storyline

The theme of our summer camp was ***'Star Wars'***, and while we did not specifically ask the participants to use ***'Star Wars'*** as the context for their spaceships, we did take inspiration from the series for our template spaceship design and also some of the UI elements such as the fonts. Therefore, it was quite natural that some participants used that as a context to design their spaceships. For instance, when P1 explored adding wings, they settled on having four wings after iterating through eight and then six wings. When asked if this was influenced by '**X-Wing**' spaceship design, they said: "*Yeah eight and six seems a bit weird, I've seen this more, so i like this.*" P4's explanation for making all the cross-sectional shapes pentagonal stars was quite interesting: "*Yes, everything's the star now. It's called the 'Star Wars' for a reason*" (Row 5, Figure. 6). Star Wars wasn't the only fictional motivation for the participants; when P10 was asked what the reason for having long wings was, they said: "*It looks like the Guardians of the Galaxy ship with the giant wings*". From these user reflections, we noted that the theme of the design task and the object did influence the way users made design decisions.

5.2.2 Experiential Participants not only took motivation from the fictional themes, but also from their past experiences. For instance, when P2 was asked why they preferred having a flat fuselage, they said: "*I wanted to make one of those cool flat ships, like a pancake*" (Row 6, Figure. 6), where they related the flatness of the fuselage to the flatness of a pancake. Similarly, when P3 used the *starry* command on a cross-sectional shape and eventually changed it to a five-pointed star, we asked them if the term *starry* made them think of a five-pointed star, to which they responded: "*Yes, when I think of the word star I think of a five-pointed star, because in general you see them on flags, you see them when you're in school and you look at them in first grade when you're looking at planets on the map and there's planets and all the stars, and stars with astronauts, and they're five-pointed stars. It's just the general picture of stars in my head*".

5.2.3 Preferential While participants made few of their decisions based on functions, fictional stories, and past experiences, quite a few of them were based on simple preferences which were mostly driven by the visual aspects of the spaceship. When P1 was asked why they were making the engines small, they answered: "*I just want the body to be big and the engines to look short and small. I don't want them to stand out*"(Row 7, Figure. 6). P5 on the other hand made bigger engines and their reason for that was: "*It's mostly just visual it looks kind of cool.*" P7, who had previously made functional and storyline-based design decisions, wanted to make their final design to be out of the ordinary: "*I'm mostly just going for something really weird really out of the ordinary, because this is such a small ship and there's so many features added to it. Because the missiles I added them to where they'd be a hundred percent bigger than what they originally were, I made the engines way bigger and I made the wings smaller for a ship that shouldn't be that small and I made the body a lot shorter to where I'm not sure if we can fit one person into it. I'm really going for something unique and very weird*"(Row 2, Figure. 5). The open-ended design task allowed users to be more visually creative, something that might have been less obvious in a specific task-driven study.

5.3 Evolution of Design Intent

One of our primary goals was to observe the evolution of design intent through iteration. Some participants iterated through only one design of their spaceship, while others designed multiple spaceships taking different approaches each time. In the initial stages of their design process, we observed some of the participants taking an exploratory approach, instead of having a fixed goal in mind. For instance, when we asked P1, at the beginning of the study, why they were going for an octagonal shape, they said: "*I was testing it out. I don't know what shape I want to go with*". Similarly, P5's response to our very first question about their design was: "*Right now I'm just mostly seeing what different things are there; I'm just exploring.*" Some participants also preferred making changes as a way to see what could be done and use that observation to make more informed choices. For instance, P3's response to the first question about their design process was: "*I was just seeing the proportions of the wings to the body and trying to get the proportions right on that and seeing how it looks with all the wings.*" For participants who designed more than one spaceship, we also observed how their design intents evolved after each spaceship. For instance, in P7's first design, they opted for a smaller spaceship, that could house a small pilot, with the aim of avoiding getting hit by the enemies. In their second design they went for a relatively bigger spaceship and which they said they could fit a team of two pilots instead of the one in their first design. For their third and final design, their goal was to make the spaceship '*really weird*', and as a result made the fuselage decagonal, added six extra wings and made the missiles twice as big as the default size. P4 took a similar approach by constantly improving the stability of their designs. Our workflow, therefore, was able to support the participants' evolving design ideas and contexts.

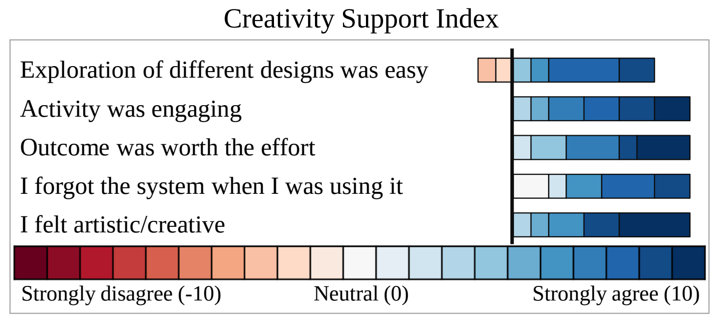

FIGURE 7. User feedback on the creativity support offered by *ShapOrator* using the Creativity Support Index. Overall feedback for our system was positive. Participants felt that the activity was engaging and made them feel creative and felt that their outcomes were also worth the effort. Two participants found the exploration of different designs to be somewhat difficult. One of the users had trouble with the vocabulary of shapes while the other felt the speech recognition wasn't very accurate.

5.4 Overall User Feedback

We received an overall positive feedback, where most participants responded warmly to the design activity and our modeling interface. Their responses to the Creativity Support Index (CSI) were also fairly positive (Figure. 7). All users agreed that the activity was engaging and made them feel creative and their outcomes were also worth the effort. Two users found the exploration of different designs to be somewhat difficult. One of them found the exploration of shapes difficult as they used the plural form of shapes (e.g., squares instead of square) in their commands and our interface was unable to act on those commands. The other user found that the interface wasn't able to recognize their speech very well. However, both the users found the experience fun and interesting and were able to create the shapes that they wanted. Users also commented on their experience using the system and completing the design tasks. P2 mentioned: "*I felt the amount you could change with voice commands alone to be fascinating. I liked making the parts starry at first then turned away from that path*". P7 commented on the ease of using their speech to make changes and related it to their class activity: "*I thought it was really cool, I haven't done something like this before. I have done coding stuff in class and I have always wanted to use my mouth because its always more convenient. Because you have the thoughts in your mind and you can say it but can't note it down sometimes.*" Along with their general feedback, participants gave suggestions on some of their desired functions. These included the ability to change color of parts, change individual components instead of only group-based changes and the ability to use words relating to 3D shapes such as cubes, cones and cylinders.

6 Discussion

6.1 Potential for Analogy-based Iterations

Design transformation in our system is initiated through a 'form-based' intent expression, i.e., we require the users to explicitly mention their desired form (shape) in their intent. The verbalization, therefore, is about the form and not the functionality of the object. However, as we noted in our results, the reasoning behind a lot of the shapes and forms that the users explored, were tied to their functionality, which the users explained in the verbal reflection phase of their design iterations. While verbalization was about the form, it made the users think in terms of function. In interactions such as sketching, this aspect of functionality is internalized and is implicit. Verbalization, therefore, plays a critical role in expressing design intent. One way of expanding the users exploration options is by enabling verbalization of analogical reasoning and translating that to a form. We can take inspiration from design-by-analogy, a methodology that has been widely studied in design theory [42], where users generate designs based on analogies drawn from desired functions or structures and so on. Computational support of this can be very beneficial in helping users in generating new designs and concepts. From our observations through the verbal reflection process, we observed the participants derive analogies and develop analogical reasoning to explain and justify their design decisions. A wide range of opportunities can be made available by integrating analogical reasoning from fields such as bio-inspired design [43], into verbalization.

6.2 How do we really talk about designs?

An important aspect of verbal inputs for design that was revealed in our study was that users invariably preferred exploring the design space by describing the function, behavior, and attributes of a design rather than directly specifying the form. This is quite natural as we typically think in terms of what we want from a design (reflection) and internally embody those preferences into the appropriate form. P3 referred to this in terms of "*naturalness*" of the speech interpretation, stating that: "*I think there should be a sense of naturalness to it, but there should also be a sense of using percentages and using specific terms for the body parts, like using casual terms to address the [parts], so not like calling them natural things but just talking about them [parts], like make them bigger. It's nice you incorporate bigger, smaller, narrower, terms you use in a regular conversation, to the thing [system], because that makes it significantly easier than saying 'make it 20 percent larger in the x direction'*". Even though our system was based on semi-natural description of shapes, it offered us a means to gain meaningful insight into how we may develop future verbal workflows that might be able to predict the form based on the description of function, behavior, and attributes.

7 Conclusion & Future Work

Our main goal in this work was to operationalize and study verbalization as a medium to enable 3D design iterations, specifically for younger audiences. The motivation behind this work stemmed from the fact that externalization of verbal inputs to explore ideas, while important, has been little studied and understood. As such, we set out to accomplish two main tasks: first, develop a system that could enable simple geometric changes to 3D shapes using verbal inputs and second, to observe and form a fundamental understanding of how verbalization enabled young designers to make design iterations. As a result, we first developed *ShapOrator*, a workflow that allowed users to explore and transform 3D shapes by giving verbal inputs. Next, we conducted a user study with 10 middle - and high-school students who were given an open-ended task of designing spaceships using our *ShapOrator* workflow. Through our user studies, we were able to show that verbalization, even when externalized through 'forms', allowed the participants to develop functional as well as topical understanding of their designs. Furthermore, we were able to explicitly highlight the design iteration process that the users followed through their reflective descriptions of their spaceship designs. We specifically showed the information and knowledge that the users associated with their workflows and how it motivated them to make further changes to their designs. These observations make a strong case for utilizing verbalization in creativity support systems, that typically use sketching, multi-touch, and gestural inputs.

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