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Affective, Hand-Sculpted Glyph Forms for Engaging and Expressive Scientific Visualization

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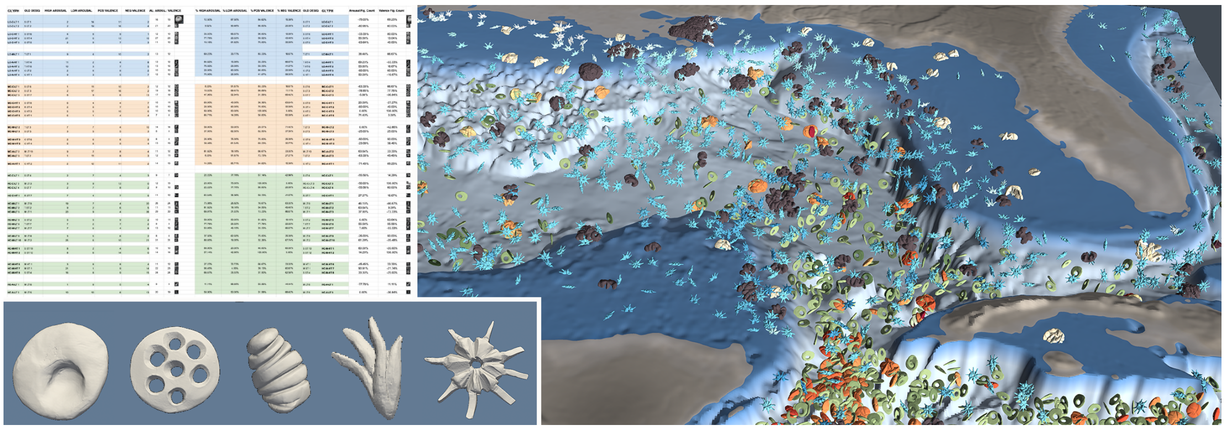

Figure 1: The upper left image shows a sample of our analysis of the 87 glyph-forms involved in our primary affect study. The lower left image shows glyph-forms frequently selected by study participants. The right image is an example of our hand-created glyph-forms from our study mapped to sampled, multivariate biogeochemistry data in the Gulf of Mexico [1].

Abstract

As scientific data continues to grow in size, complexity, and density, the representation scope of three-dimensional spaces, data sampling methods, and transfer functions have improved in parallel, allowing visualization practitioners to produce richer multidimensional encodings. Glyphs, in particular, have become an essential encoding tool due to their versatile applications in co-located multivariate volumetric datasets. While prior work has been conducted investigating the perceptual attributes of computationally-generated three-dimensional glyph-forms for scientific visualization, their affective and expressive qualities have yet to be examined. Further, our prior work has demonstrated the benefits of artist hand-created glyph forms in contrast to commonly-used synthetic forms in increasing visual diversity, discrimination, and expressive association in complex environmental datasets. In order to begin to address this gap, we establish preliminary groundwork for an affective design space for hand-created glyph forms, produce a novel set of glyph-forms based on this design space, describe a non-verbal method for discovering affective classifications of glyph-forms adopted from current affect theory, and report the results of two studies that explore how these three-dimensional forms produce consistent affective responses across assorted study cohorts.

Keywords: Glyphs, affect, visualization, scientific visualization, art

1 Introduction

Data visualization has traditionally been defined as the use of graphical and spatial representations mapped to data attributes to facilitate visual reasoning and investigation. Research into scientific visualization techniques has largely focused on perceptual efficacy and on maintaining minimum obstructions or disturbances to the base data in order to most quickly and accurately evaluate its shape, and—particularly in large, environmental simulation data—relationships between variables over time. However, speed and fidelity of perception encompass only a small portion of the factors that contribute to our understanding of visualized scientific data.

Affect plays a significant role in communication, engagement, and problem-solving for all categories of visual imagery. The emergent, affective quality of any image—composed of specific color, shape, form, composition, and textural properties—amplifies, augments, and moderates our sensemaking concerning its content. The ability to metabolize and react to complex visual landscapes has been written into our visual systems over the course of thousands of years of evolution, made more effective by the production of informative associations with specific emotions and sensations. Brighter and more saturated warm hues signaling danger or significance draw our attention quickly; highly-textured, pointy objects index fear and and recall pain from early-childhood experimentation; slight shifts in the hue and shape of cloud formations alert us to coming storms and changing seasons (while dark, towering, and imposing cumulonimbi inspire the desire to take shelter, softer, more wistful, and lighter-hued cirrus suggest a calmer atmosphere); highly-developed texture and pattern recognition allow us to locate edible plants amongst throngs of their illness-inducing counterparts. For thousands of years, artists have drawn on this innate skill for parsing visual complexity to communicate specific messages via specific affects. In order to direct this visual processing power toward specific, communicative ends, however, artists are trained to selectively reduce the complexity of our environmental surrounds to access and reproduce the essence of their affective and associative qualities. The French impressionists employed this technique to convey the emotional atmosphere (or, "impression") of a physical place through strategic use of color and reduction of fine detail.

Visualization practitioners apply similar techniques, working from the pre-existing composition provided by the data and using color, shape, and texture to enable efficient exploration and extraction of information. As in art and in life, rather than neutral, inert, or

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sterile, each component of a visualization instead indexes specific experiences, emotions, memories, and instincts for the viewer. While significant work has investigated such affective qualities produced by color in both information [2] and scientific visualization [3], comparatively little research has studied the affective qualities of independent glyph forms. As scientific data continues to grow in both size and complexity, the representational scope of three-dimensional spaces, data sampling methods, and transfer functions has improved in parallel, allowing visualization practitioners to produce richer multidimensional encodings. In particular, glyphs have become an essential encoding element for multivariate, three-dimensional visualization, where they are used to map categorical attributes for improved intra-variate discrimination. Scientific visualization programs including ParaView and VisIt provide several basic glyph encoding options: spheres, cones, cubes, rods, and arrows. However, these options can limit both the discriminatory power and the communicative efficacy of multiple co-located variables in three-dimensional space. Our prior work investigates the potential benefits of applying established techniques from the arts to the creation of glyph forms, enabling both more effective intra-variate discrimination and communication through visual balance and semi-abstract association. We found that generating glyphs using clay and the human hand drastically increased the range of possible glyph forms and their qualities, and therefore the number and type of possible data encodings [3]. But what kind of affective impact do these highly diverse, hand-created forms carry? Might we be able to craft affect impressions for specific communicative aims using methodologies from design, gestalt, and affect theory? Towards this end, we present an exploratory investigation of the affective qualities embedded in a set of 87 hand-created clay glyph forms. The work reported in this paper makes four contributions:

1. We report results from two studies that explore how 3D glyph forms contribute to affect;

2. We establish preliminary groundwork for an affective design space for glyph forms in scientific visualization;

3. We produce a novel set of glyph-forms based on this design space;

4. We describe a non-verbal method for discovering affective classification of visual forms adapted from affect theory [4].

By mingling art and design with computation—bridging physical spaces and objects with their digital counterparts—we explore the overlaps and intersections that provide not only richer encoding schemes, but also more meaningful, visceral connections to data.

2 Related Work

2.1 Affect and Sensemaking

Affect, how we feel and respond emotionally to objects and environments, forms an essential aspect of communication in many spheres. Evoking an appropriate affective response is essential to creating immersive and engaging experiences in art and, increasingly, in science. We metabolize external phenomena through two information processing systems: the *cognitive* and the *affective*. Affect is commonly defined as an unconscious reaction of feeling or emotion before any cognitive appraisal of an event occurs [5]. The cognitive system interprets and makes sense of input from the world; the affective system rapidly "judges" the environment according to factors such as valence, excitement and threat [4, 6] resulting in a mood, feeling or impression. These are often described by the well-known PAD model of affect [7] that plots them in a parametric space defined by pleasure (valence) and arousal dimensions (Figure 2). The Valence axis covers the hedonic range, from positive (happiness, pleasure, love) to negative (pain, anger, sadness, fear). The arousal

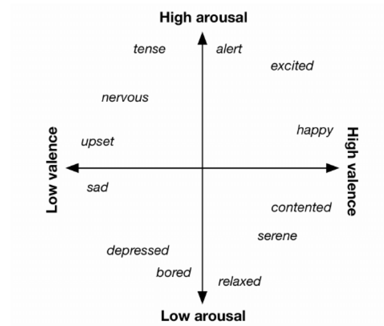

Figure 2: The PAD model of affect [7]

axis reflects intensity from quiet (unaroused, relaxed, sleepy, etc.) to excited (high arousal, stimulated, nervous, alert, etc.). Typical emotions such as surprise, disgust or compassion can be placed in this 2D space. Extensive emotion research has defined many more nuanced affects (such as affection or boredom) in this model as well [8]. But these systems are not completely independent: emotion can result from cognitive reasoning, and affect influences cognition. Evidence shows arousal enhances memory: experiences that elicit arousal are more likely to be remembered than ones that do not [9, 10]. However, this differs with valence: negative events are remembered with greater detail than positive events [10, 11]. Affect also influences sensemaking strategies: there is evidence that positive affect promotes creative thinking and facilitates problem-solving [11–13].

2.2 Affect in Visualization

While there is a long history of research and practice in how visual elements and structures relate to affect in art, design, marketing and psychology (see [2] for a review), there is relatively little research in how affect can be incorporated into data visualization design for more expressive and engaging experiences. Harrison explored the impact of emotion in visual analytics design [14, 15]. More recent work in data storytelling [16, 17] has begun to explore the role of designing for richer rhetoric and affect in data narratives. Of note is work that specifically examines the importance of empathy [18] and trust [19] in visualization. However, we still have few guidelines for how visual features and structures can be applied affectively in visualization design. Bartram et al. [2] and later Anderson et al. [20] identified features of affective color palettes for categorisation in information and geographic visualizations. Other researchers have examined motion and animation properties for affect [21, 22]. There is yet, however, little or no research into how object properties related to form (shape and texture) contribute to affective impressions in the context of visualization.

2.3 Glyph systems

A similarly long history of research and practice exists in the study of glyph systems for scientific visualization. Glyphs are critical to understanding the distribution and density of materials and properties over time and space, particularly in multivariate, volumetric datasets. These glyphs differ from information visualization and cartography—while they must be three-dimensional to accommodate the data, they are not encoded by dimension. Instead, these glyph-forms must be diverse enough to effectively discriminate from each other in space, simple enough to avoid visual cacophony, and evocative enough to communicate specific information about the data they encode. Traditional scientific visualization applies basic geometric forms—spheres, cubes, rods and arrows—to delineate attributes of point data, leaving color to represent scalar variables. The selections in commonly used visualization software such as ParaView limit users to these four options.

Significant work has addressed the production and use of glyphs for two-dimensional visualization. Research in three-dimensional visualization focuses primarily on variety, direction, and scalar value representation [23–25]. Kindlemann et. al.'s work demonstrates examples of mathematically-constructed glyphs for scalar representation that morph to show a scale value and/or a direction in space. [26–28]. Composite shape systems have also been developed to address categorical needs [29].

Despite these advances, little work in scientific visualization thus far has addressed glyph properties outside of their perceptual or encoding value, such as holistic design qualities, gestalt spatial reasoning, or affect. Here, we are stepping back from perceptual differentiation [30, 31], mathematical representations, explorations into metaphor [32], semantic association, and artistic application [3, 33] to consider the inherent affective properties carried by diverse sets of hand-created forms for scientific visualization.

2.4 Form from Function, Affect from Form

For centuries, artists and designers have been trained to manipulate form to imbue an image or object with affective impact. Classically, *shape* is used to describe the 2D abstraction (such as circle, square or line) of a 3D *form* [34]. Forms have important properties including shape, texture, tactility, complexity, and qualities related to provenance: origin (is it "natural", organic or mechanistic?); and production (is it hand made? engineered?). These properties relate strongly to both recognition and affect. We immediately identify shapes from their most simple and abstracted (canonical) representation [35]. The distinction between lifelike and mechanistic underpins how humans interpret the world [36]. The form doesn't have to be recognizably real to be considered plausibly organic: we can recognize properties similar to something already known and generalize (e.g. "this looks like bread"), a process known as analogical reasoning [37]. However, recent research suggests that extremely lifelike forms may be less suitable for encoding data attributes: Pandey et al. found that subjects are more accurate with a less anthropomorphic glyph, and that anthropomorphic glyphs introduce biases due to their anatomically salient features [38]. Simple geometric properties such as roundness, angularity, and complexity have been shown to influence affective responses [39–41]. In particular, v-shaped objects that point toward the ground elicit a strong negative reaction [42, 43]. Results from a study by Isbister et al. showed that rounded shapes correspond to positive valence, spiky shapes to negative valence, smooth shapes to low arousal, and protruding surfaces to high arousal [44] However, affect research overwhelmingly confirms the affective potential of more complex animate or "natural" forms [42, 45]: people prefer these to more mechanistic forms that are often seen as more negative and stressful [42]. Finally, as Norman notes [46], people respond more positively to imagery or artefacts that appear to have been made with care, manifesting a property of quality. This is no news to the artists, who recognize the importance of these kinds of forms as valuable signs in their own right rather than as the combination of potential visual features for mapping data attributes.

3 User Studies

To better understand how three-dimensional, hand-created forms relate to specific affective responses and which attributes contributed to these responses, we conducted two sets of studies using a convenience sample of University of Texas students and employees. We created sets of glyph-forms that we asked our participants to evaluate in terms of affect. The results of the initial study informed the redesign of the glyph-forms set used in the second study. Both studies used the same method and set-up.

3.1 Methodology

Our first challenge was determining how to capture and evaluate these affect-form associations. Evaluating affect, and its related features, is challenging for a number of reasons [4]. Researchers have devised a number of different methods and instruments to measure affective properties. These methods take two different approaches to tasking participants with expressing the relationship between object and affect:

1. Given an image or object, the participant describes her affective reaction. Because of the variability in verbal descriptions, researchers have developed non-verbal instruments, such as the commonly used Self-Assessment Manikin of a human figure with 18 different facial expressions [47] or the richer pictorial International Affective Picture System [4]; or

2. Given a set of specific affect categories (such as "frustration", "pleasure", "excitement" etc), the participant selects design features to match the affect. This method was used recently in studies of 3D shape [41] and colour palettes [2].

Recent studies close to our own goals in understanding the relationship between affect and form used the second approach [2, 41]. However, we wanted to explore affect-glyph-form associations in which we did not pre-define specific affects, but rather located them in the overall 2D valence and arousal space. We adapted a method from the design of the standard IAPS instrument commonly used in the first approach. The IAPS is a large set of standardized, emotionally-evocative, internationally accessible color photographs that includes content across a wide range of semantic categories. It was constructed through participant placement of images on a spatial scale defined by valence, arousal and dominance. The IAPS can therefore be considered a parametric assignment of image to location in affect space, reducing the variability of how people interpret the nuances of particular emotion labels.

We based our method on a simplified version of the IAPS model in which we asked participants to place photographs of our 3D glyph-forms in a 2D PAD space defined by a horizontal valence axis (labeled Negative-Positive) and a vertical arousal axis (labeled Calm-Exciting). Participants chose glyph-form images to place within the axes, and were not limited by the number of images they could choose (See Figure 3).

We chose to use images of the original, three-dimensional small clay sculptures, rather than the objects themselves, to avoid confounding this exploratory work with the much broader range of variables, or form-qualities, presented by physical objects, including size, weight, texture, and material. Further, though three-dimensional glyph-forms may represent data in three-dimensional space, they are still viewed in the two-dimensional environment of a computer screen. Therefore, we shot photos of each individual glyph, placing them in identical lighting situations against a black background. Further post-production work included close-cropping in a square aspect ratio in order to provide a consistent size for each image.

3.2 Study Set-Up

For each study, We set up one large table in a public space with two axes and labels as shown in Figure 3. A second large table with all the glyph-form images distributed randomly was placed adjacent to the axis table. We gathered participants via a random convenience sampling of those passing through the lobbies of university buildings throughout the morning and early afternoon. Each participant was given a brief overview of the focus of the work, then asked to choose any number of form images from the table and to place them within the axes based on the affect they felt was produced by each glyph-form image, treating the axes as continua rather than as discrete quadrants. We encouraged the participants to work intuitively, and to stop when they no longer felt strongly about any of the remaining forms. When each participant had concluded their form image placement, we took a photo of the results, provided

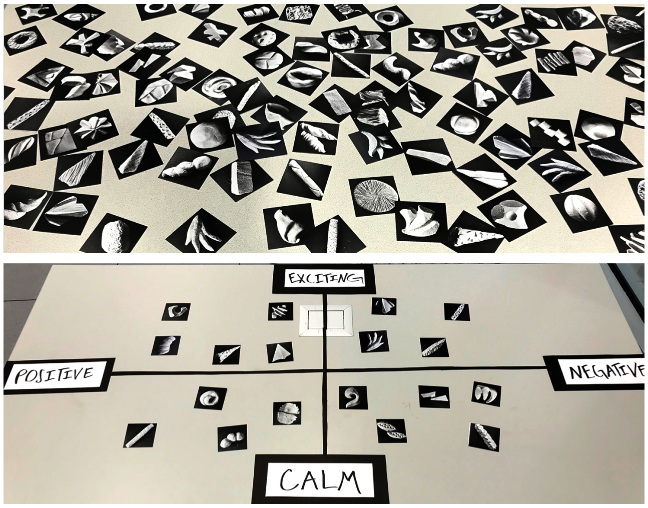

Figure 3: Participants selected images randomly arranged on one table and placed them within the affect space on an adjacent table.

the participant with an iPad, and asked them to elaborate on their choices by annotating the results photo.

4 Study 1:pilot

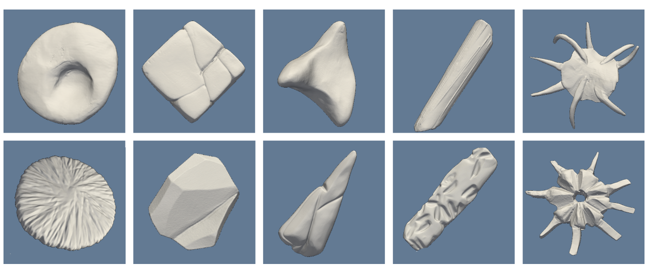

Figure 4: Examples of hand-created glyph-forms derived from an underlying set of ”base” forms. From left to right (both rows): sphere-derived form, cube, cone, rod, and a form with a combination of features. The top row shows glyph-forms with less dense texture, while the bottom row shows forms with more dense texture.

We began with a small pilot study of a set of 112 images of hand-created, clay forms, previously produced for work focused on expanding the visual vocabulary of complex, multivariate environmental visualizations [3]. The primary purpose of this pilot study was to acquire a sense of the reactions to our existing glyph forms and whether the dimensions of base shape and texture influenced placement within the 2D affect space.

We set the pilot study up in the lobby of the Texas Advanced Computing Center’s main building and recruited 25 employees to participate.

4.1 Pilot Study Results

Of the 112 glyphs placed on the table, 88 were used by the 25 participants. Twelve were used 5 or more times, while 24 were never used. Of the 12 most-used, the majority were perceived as possessing some specific associative property or properties. Based on verbal and written participant self-narration and responses, this association played a large role in whether the form image was chosen and where the image was placed. For example, the form in the lower left of Figure 4 was consistently compared to a sand dollar, was used 14/25 times, and was placed most often in the positive side of affect space. The furthest right form in the top row of Figure 4 was often compared to a primordial organism. In contrast, many of the forms that were never used by any of the 25 TACC participants were highly abstract, with no clear analogue to either natural or artificial phenomena. The participants’ written responses focused largely on the forms’ associative properties, rather than either feelings produced by the forms or positive, negative, exciting, or calm attributes inherent to the forms themselves. Further, participants tended to place more forms in the positive sections of the axes rather than the negative.

4.2 Pilot Discussion

The results of this study provided several insights that informed our approach to both glyph creation and to the study design. We were somewhat surprised to see that with the exception of the round sand-dollar form, these basic forms did not substantiate affective associations identified in previous research, aside from a strong preference for anthropomorphic forms. Participant feedback strongly suggested that the primary determinant was the real-world analogue the form suggested. This may explain why most glyphs were placed in the positive quadrants: partially the result of choice bias—the tendency of participants to gravitate toward forms they felt positively about, appreciated aesthetically, or produced positive real-world associations. The lack of negative form placement may also have been due, in part, to the lack of inherently negative forms available in the selection group. While significant work has been done to test the strength, consistency, and accuracy of association between abstracted or cartooned forms and their real-world analogues (with [35] as the seminal study) comparatively little work has been done, particularly in visualization, to investigate the affective properties of abstract forms that do not elicit consistent, specific associative imagery. While we did not expect responses of the pilot to be so strongly oriented toward semantic association, this result suggested that future studies would require more abstract forms in order to investigate whether native properties carried by specific characteristics, and combinations of characteristics, of non-associative forms would produce consistent affective responses in a variety of subjects. Further, the lack of relatively equal distribution of forms across quadrants demonstrated the need for a new set of abstract forms that were constructed specifically with the four affect categories in mind; i.e. forms that, drawing from established design, gestalt, and affect principles, would theoretically lend themselves to positive, negative, exciting, and calm affective responses.

5 Glyph Form Design: Take 2

These results caused us to rethink our fundamental taxonomy. In order to achieve better distribution and consistency, we generated a set a new set of 87 hand-produced, clay forms, according to prior work in design, gestalt, and affect theory.

We chose to limit form material to clay, as in the pilot study, in order to maintain consistency of appearance and to imbue the forms with the quality of being ”hand-made” (See Figure 6). We began with sets of “blanks”—spheres, cubes, cones, and rods—to construct the second set of glyph forms by hand. This method draws on design practice involving both the standard elements of design theory—line, shape, form and texture—as well as employing an iterative, exploratory methodology, building up from the most basic forms and compositions to achieve balanced complexity. We extracted from these shapes, creating a variety of forms incorporating a selection of gestalt principles—enclosure, symmetry, and continuity—and affective principles—”pointiness” or perceived sharpness, curvature, and texture. Rather than basic shape as a category, we arrived through this process at three key attributes of our forms: curvature (curved, angular, mixed); complexity (low, medium, high); and texture (sparse, dense). (We note that complexity, in particular, has recently been identified as an affective element in image

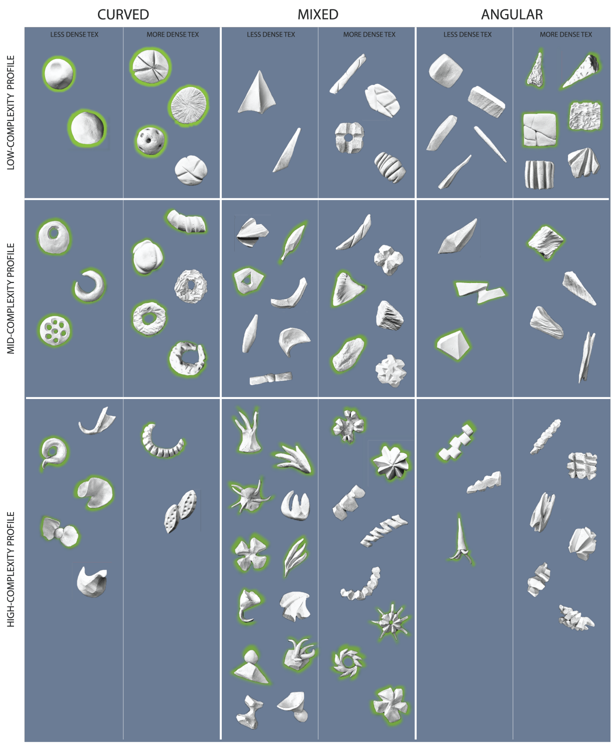

Figure 5: All 87 hand-created glyph-forms used in our second study are organized here by descriptive category: curved, mixed, or angular components (horizontal axis); low, mid, or high-complexity profile (vertical axis); and less or more dense texture (secondary horizontal division). Glyph-forms highlighted in green were used 8 or more times by participants. Those not highlighted in green were used fewer than 8 times.

categorization [39].) The full set of clay glyph forms is shown in Figure 5.

6 Study 2

We conjectured that our new set of forms would provide relatively clear distributions across affect categories, roughly adhering to the principles of affect in prior work. We anticipated that forms with pointier elements dominating their profiles, along with less curvature, would tend to be exciting and negative, while more rounded forms, or predominantly curved profiles, would produce a calmer affect; simpler and rounder objects would be more positive; and more textured forms would be more exciting, while less textured forms would be calmer.

We also increased the scope of our participants to include both people in the liberal arts and the engineering disciplines, on the premise that perhaps background substantially influenced the tendency toward semantic association so prevalent in the first study. We solicited participation in the liberal arts building and the engineering building on UT's campus, along with the Texas Advanced Computing Center's building, and recruited 32 participants in liberal arts, 19 in engineering, and 8 at TACC by random convenience sampling.

6.1 Results

We present preliminary results and analysis. The forms are defined based on their categorizations within the organized grid shown in Figure 5. We focus on the forms that were used a total of 8 or more times by participants across groups, comprising just under half of the set. Figure 7 illustrates the results of glyph placement across

Figure 6: Artists draw inspiration from source material to broaden the range of form and texture in their work. Here, Samsel draws from natural imagery to inform her hand-sculpted, clay glyph-forms, which will later be 3D scanned and used as data encodings in multivariate, volumetric visualizations.

all participants, while Figure 8 shows a selection of the most used glyphs discussed in greater detail below.

6.1.1 Calculating affect quadrant location

Rather than calculate exact individual glyph distance and location in affect space, we categorized glyph placement by four quadrants: Q1 (negative-exciting), Q2 (positive-exciting), Q3 (negative-calm), Q4 (positive-calm), and Neutral (the image was placed directly on an axis line, or in the center, at the point of intersection of the two axes). We coded the Neutrals in 5 categories: Exciting, Calm, Negative, Positive, and True Neutral (at the intersection point of the axes). We first calculated the total placements in terms of arousal (exciting-calm) and valence (negative-positive) by summing across quadrants, then taking the percent usage from the total usage in both arousal and valence categories for each form. Uses of each form were then counted by individual quadrant, regardless of where in each quadrant they were placed.

We totaled the number of participant uses per form per quadrant, then calculated the percentage of uses per quadrant for each form. Here, we consider any percentage over 40% to demonstrate significant grouping for quadrant counts, and over 50% for valence and arousal. Negative values were assigned to calm arousal quadrants and to negative valence quadrants, while positive values were assigned to exciting arousal quadrants and to positive valence quadrants. The total percentage use for a glyph-form's arousal and valence positioning was then calculating by summing the two values for each category. For example: The crescent moon glyph-form in the bottom right corner (MC-C-LT2) of Figure 8 was placed in high arousal quadrants 10.53% of total uses and in low arousal quadrants 89.47% of total uses. Its arousal placement total is therefore -78.95%, resulting in its placement in the bottom row on Figure 5. This form was also placed in positive valence quadrants 88.89% of total uses, and in negative valence quadrants 11.11% of total uses, resulting in a total valence value of 77.78%. The form was therefore placed in the rightmost column of the graph. Its final combined position is the bottom right corner square, indicating that the crescent glyph-form was placed in calm, positive quadrants almost every time it was used.

6.2 Analysis

Figure 8 shows the specific glyphs referenced in this section. Our results demonstrate several interesting trends. First, we noticed some encouraging consistency across our categories of complexity, curvature and texture. Of the 10 low-complexity profile forms, 5 demonstrated 60% or more grouping in low arousal quadrants, and 8 demonstrated 50% or more grouping in positive quadrants. 4 of the 5 with significant grouping in high arousal quadrants were classified as densely textured with angular components.

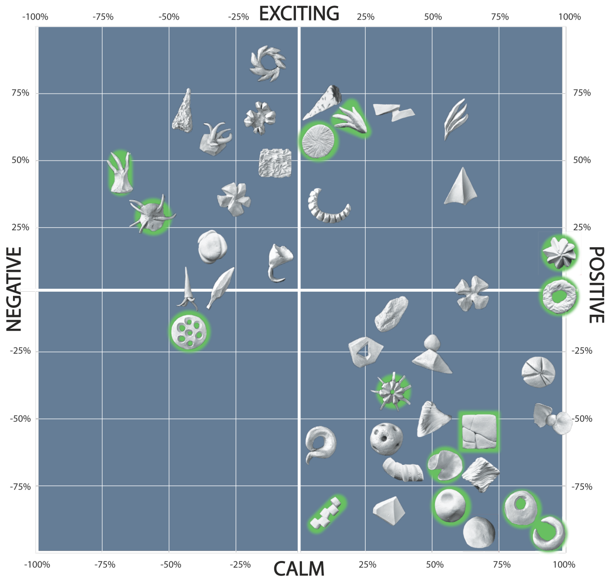

Figure 7: As described in section 6.1.1, this figure shows only glyph-forms used 8 or more times, plotted within the two-dimensional affect space based on percentage of quadrant placements for each glyph-form, across all participants in our second study. Glyph-forms highlighted in green are those discussed in the Results section and correspond to those shown in greater detail in Figure 8.

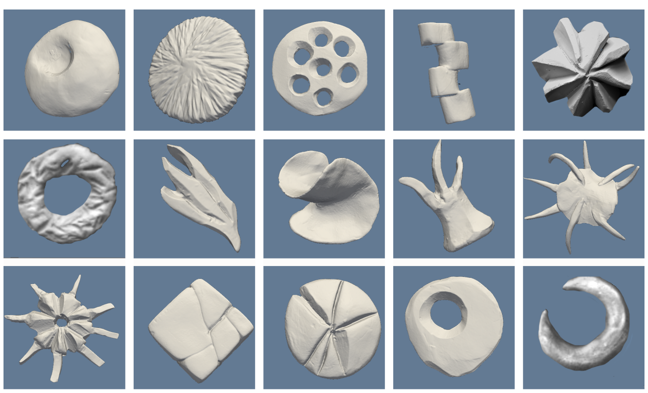

Figure 8: Glyphs discussed in the Results section. Top row: LC-C-LT1, LC-C-HT2, MC-C-LT3, HC-A-LT1, HC-M-HT2. Middle row: MC-C-HT3, HC-M-LT6, HC-C-LT4, HC-M-LT1, HC-M-LT3. Bottom row: HC-M-HT6, LC-A-HT3, LC-C-HT1, MC-C-LT1, MC-C-LT2. Refer to supplementary material for greater detail and a complete list of glyph-form labels.

Of the 14 mid-complexity profile forms, only 4 demonstrated significant grouping in negative valence quadrants, while 11 forms demonstrated 50% or more grouping in positive quadrants. Form MC-C-HT3 was placed in positive quadrants 100% of uses. In general, angularity and curvature did not produce as significant an effect on arousal placement in mid-complexity profile forms as in low-complexity profile forms.

The high-complexity profile forms demonstrated greater distribution across quadrants than the mid- or low-complexity profile forms. HC-M-LT6 and HC-M-LT3 were the most consistently-placed forms, with grouping concentrated in Q2, the exciting-positive quadrants, and Q1, the exciting-negative quadrants, respectively. High-complexity profiled forms were also placed in neutral

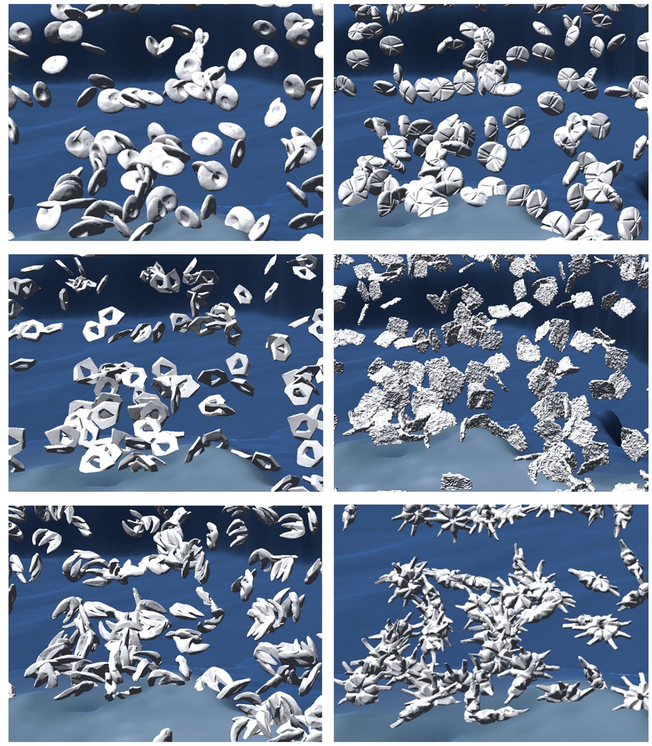

Figure 9: A comparative set of images illustrating the concept of cumulative or emergent affect. The left column shows glyph-forms with low-density texture; the right shows high-density texture, each with varying profile complexities and curvature attributes. When applied to data, these forms may occupy volumetric space in unexpected ways, overlapping and combining to produce new, more complex forms.

positions more often and with greater consistency: HC-A-LT1, for example, demonstrated grouping in neutral locations 33% of the time. These placements were distributed across the calm axis, the negative axis, and the true neutral position. Verbal feedback reflected this trend; many participants expressed both interest and confusion concerning this form, and tended to identify it as either broken, and therefore negative, playful, and therefore positive, or some marriage of these elements, and therefore neutral.

Of mid- and high- complexity profile forms that were used 8 or more times, most demonstrated significantly less grouping and more spread across arousal and valence quadrants if they had mixed angular and curved components.

In general, the top 12 most-used forms had either highly complex profiles with both angular and curved elements, or extremely low-complexity profiles with primarily curved elements. These forms were either very neutral and calm, or highly distinct and irregular. A majority of these forms were placed with over 50% consistency in a particular quadrant.

We also noted interesting patterns related to complexity and affect. Of the 10 shapes used 8 or more times with low-complexity profiles that adhere most closely to simple spheres, cubes, cones, or rods, 5 were placed most often in the calm-positive quadrant, Q4. The likeliness and consistency of placement in Q4 across this category decreased with the level of texture and the angular quality of the forms, with the exceptions of LC-A-HT3, which was placed in Q4 almost 73% of the time when used, and LC-C-HT2, which was distributed throughout all four quadrants and most often appeared in Q2, the positive-exciting quadrant. Based on verbal feedback, the former's highly even, square form represented calmness, tranquility, and stability for a majority of participants, despite its lack

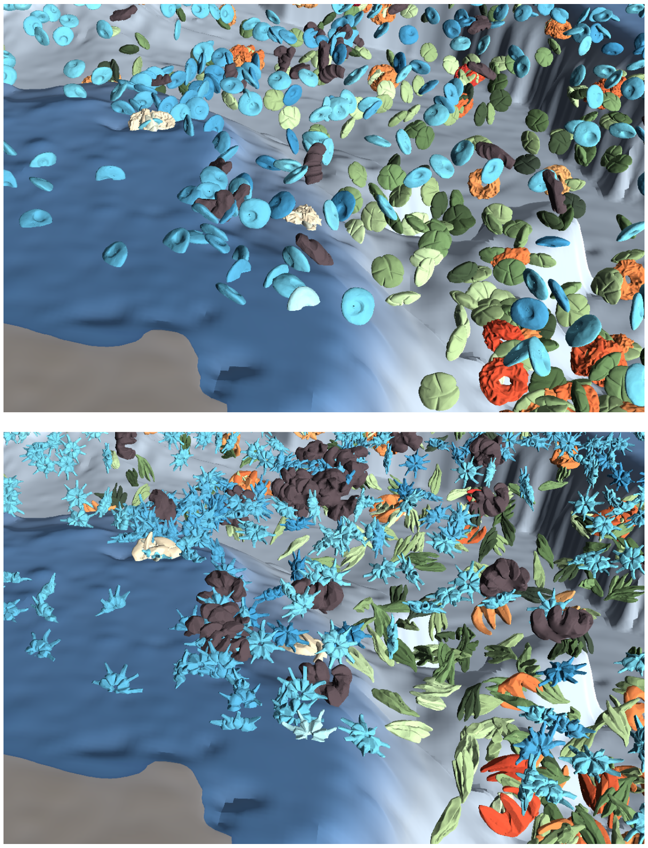

Figure 10: A comparison of glyph-forms from two different attribute classifications mapped to multivariate biogeochemistry data in the Gulf of Mexico. The top image shows glyph-forms of varying textures with low-complexity profiles and curved attributes that were most often placed in low-arousal quadrants. The bottom image shows glyph-forms of varying textures with high-complexity profiles and primarily angular attributes that were most often placed in high-arousal quadrants. Colormapping is consistent between images; only the glyph-forms have changed.

of curvature, while the latter's shape and markings reminded many participants of a sand dollar—a positive association for most—with high-density texture, which tends to produce an exciting affect. The two most consistently-placed forms with low-complexity profiles were LC-A-HT3, this square form, and LC-C-LT1, a spherical form with a small, finger-sized divot. 8 of the remaining 9 forms were each clustered with over 40% consistency, with the angular, highly-textured forms clustering more often in Q1, the negative-exciting quadrant.

Of the mid-complexity, curved, low-texture forms, two — MC-C-LT1 and MC-C-LT2 — had both extremely consistent placement and high usage counts. The third member of this category, however—MC-C-LT3—demonstrated extremely dispersed results, with the majority of uses falling either in Q1 or Q4. Based on verbal feedback, this form was disturbing to many participants, who often cited trypophobia—the aversion to irregular patterns, clusters of small holes, or bumps. This phobia accounts for the form's high negative-exciting placement. In contrast, others who did not experience trypophobia found the form playful and positive, placing it in Q1 almost equally as often. Of the 15 mid-complexity profile forms, only 4 demonstrated less than 40% placement consistency. Further, every form categorized as mid-complexity profile, curved, and highly-textured was used 8 or more times, and all but one was placed with over 40% consistency across quadrants. The most-used mid-complexity profile forms exhibited fewer placement trends than the low-complexity profile forms, though the most-used quadrant remained Q4.

Of the 19 high-complexity profile forms, 11 demonstrated over 50% grouping in positive valence quadrants, with forms HC-M-HT2 and HC-C-LT4 both placed in positive quadrants 100% of the time. For high-complexity profile shapes, more dense texture tended to indicate higher arousal, while less dense texture correlated with lower arousal. Several of the most-used shapes had both high-complexity profiles and significant grouping—HC-M-LT1 and HC-M-LT3, for example, showed 73.08% and 68.97% placement in high arousal quadrants and 80%+ in negative valence. In contrast to what we might expect, based on these trends, form HC-M-HT6 was placed in low arousal quadrants almost 73% of the time and in positive quadrants nearly 67% of the time. This outlier result can be partially explained by the verbal feedback of participants: many stated that this particular form reminded them of the sun, an association that carries a positive connotation for most. Sun icons often connote happiness or joy in American cultural contexts. This association appears to have overwhelmed the abstract qualities of this form that would otherwise have influenced its placement in negative valence and high arousal quadrants along with similar forms with similar qualities.

7 Discussion

Many new directions and areas of refinement arose during the course of this work. Explorations have begun in three directions: associative glyphs, materials, and exaggeration of affective characteristics.

Our results are preliminary, and deeper analysis of the data is beyond the scope of this paper, though we intend to address it in future work. Nonetheless, they open the door to a set of novel and fascinating insights and questions with significant potential for the scientific visualization community. Primarily, they affirm prior work in affect theory and extend it to artistic expressiveness in scientific visualization [48]. Roundness, angularity, complexity, and simplicity influence affective response, evidenced by the distribution of quadrant placements of diverse forms. Further, these aspects combine in specific ways to produce specific results: the more round and simple a form, the more likely it will receive a low arousal, positive valence placement. The more angular and complex, the more likely the form will receive a high arousal, negative valence placement. These results also indicate that the more anthropomorphic, or associative, a form appears, the greater the biases introduced to their placement along affect axes. Care must be taken therefore to ensure that if these biases are activated, they are least consistent! This effect is most clear with the few shapes that produced consistent associative reactions in participants, such as HC-M-HT6 (the spiky, wheeled, highly-textured form in the 25-50% calm, 25-50% positive square), which demonstrated irregular placement compared to similar forms due in large part to its consistent association with the sun. However, the anthropomorphism of a form may also contribute to its visual interest and appeal. As we are drawn—likely influenced by evolutionary traits—toward images and objects that appear organic or alive, we posit that the visibly handmade, imperfect quality of these clay forms contributed to participants' affective responses. Many commented while attending to the placement task that the forms were beautiful, warm, interesting, relatable, and strange, and asked where they came from and how they were made. Most assumed that the forms depicted in the images were real, in some sense—that they existed in the physical world as tangible objects with materiality, size and weight. The knowledge that they were not computer-generated and were instead produced by an artist and her tools appeared to further interest and gratify many participants, who proceeded with the task with a newfound appreciation of the forms and a clearer idea concerning their affect.

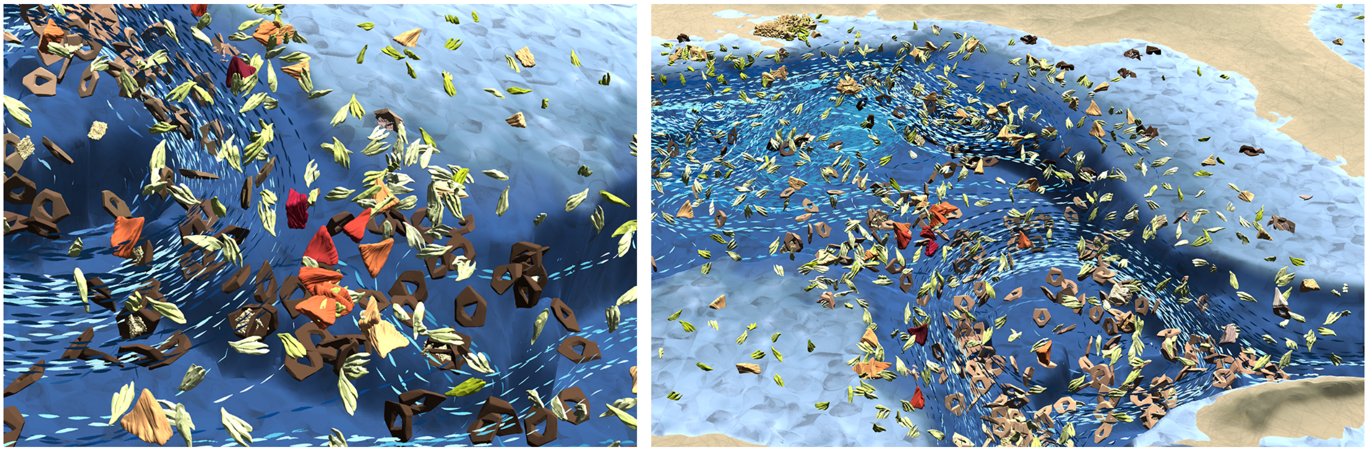

Figure 11: This figure demonstrates the value and potential use for glyph-forms tested in our second study. Here, three different glyph-forms from three different attribute categories are mapped to three different variables in E3SM biogeochemistry data in the Gulf of Mexico. The glyphs are accompanied by streamlines showing flow direction of local currents. The textured, triangular glyph-forms encoded with a red-orange color ramp are mapped to a high-concentration classification of nitrates. The semi-angular, smooth glyph-forms derived from spheres with a triangular hole in the center, encoded with a luminance ramping brown color ramp, are mapped to a second, lower-concentration class of nitrates. The three-pronged, fork-like glyph-form encoded with a luminance ramping lime green color ramp is mapped to chlorophyll. The color ramps of all three glyphs encode concentration levels of each variable respectively.

Our results also demonstrate the complexity of the relationship between form-qualities and affect. The consistency, and therefore predictability, of form placement decreases with the complexity of the form's profile. Edge-based representations mediate real-time object recognition and provide the most primary and immediate cues for visual search and recognition [49]. Here, we have shown that edge (profile) likewise plays a large role in affective response. Forms chosen for placement most often were the most distinct in their respective categories, in terms of highly complex and highly simple profiles. A majority of forms placed in negative quadrants lacked the gestalt characteristic of "enclosure"—many had long, spiky or angular tendrils; holes; multiple distinct components, indicating that two separate objects had been brought together; or were incomplete in some manner. Further, many shapes placed more often in negative quadrants were asymmetrical (outside of the slight asymmetries inherent to handmade objects). In contrast, many of the forms placed most often in positive quadrants were highly symmetrical and "enclosed," or complete, unbroken, and lacking elements resembling extremities outside the form's main body. These qualities contribute to complex affects that are essentially emergent products of the forms and their design, perceptual, and gestalt components. There is no singular, high-confidence predictor of affect placement, but rather, the components of form (or, form-qualities) produce affects specific to the emergent result of those components.

7.1 Visualization Applications

This work surfaces several significant potentials for scientific visualization applications. Our preliminary results demonstrate that these forms, rather than inert and neutral, instead carry specific qualities capable of producing consistent, specific affects in most viewers. In order to direct this affect toward specific ends, design, gestalt properties, and communicative intent must be carefully considered. Further, as large, multivariate simulation data continues to increase in size and complexity, a broader, more diverse, and more expressive visual lexicon is required to produce both analytically and communicatively useful visualizations. As we have demonstrated in prior work [3], handmade glyph forms allow for significantly more freedom and variety, increasing intra-variate discrimination, aesthetic interest, and engagement. However, this work also requires consideration of holistic design and the combined affect produced when these individual glyph forms are placed in the same digital, three-dimensional space. Figure 11 demonstrates the purely perceptual and communicative potential benefits of using these glyph-forms to meet practical visualization needs. Here, three different glyph-forms from three different attribute classifications are mapped to three different variables in E3SM Gulf of Mexico biogeochemistry data using Artifact-Based Rendering. [50] These clay glyph-forms were 3D scanned, then used to encode sampled data points in three-dimensional space. [50] The scientists using these data are interested in potential locations for macroalgae cultivation for later use as biofuel. The presence of chlorophyll is an indicator of possible cultivation sites. Here, we have encoded the chlorophyll variable with a glyph-form that was often placed in high-arousal quadrants and derived from a base cone shape with a high-complexity profile. This provides significant contrast with surrounding variables, which are encoded with glyph-forms of markedly different key attributes, and draws attention to the chlorophyll as a key variable. While beyond the scope of this paper, much work remains in investigating and flushing out the precise effects of these glyph-forms on analysis, communication, and emergent affect.

8 Limitations: Design Challenges

A primary limitation of this exploratory work is the focus of our study on examining the individual affects produced by individual glyph-forms, each presented alone and without environmental context. When glyphs are applied to data, the multiple co-located forms produce an emergent affect representing their combined composition. Which attributes of the glyph-forms contribute most significantly to this emergent affect? Are their individual affects amplified or reduced? Does the combined composition produce new associative properties for individual glyph-forms in this new environmental context? Figure 9 demonstrates how dramatically glyph choice can alter overall affect. Here, a selection of glyphs from our second study encode a single variable of Gulf biogeochemistry data. Groupings of the sphere-based glyph-forms, shown in the top row of Figure 9, maintain a simple, rounded profile and therefore, we posit, a calmer combined affect. In contrast, glyph-forms with more complex profiles, as shown in the bottom row of Figure 9, produce new, combined forms with increasingly complex profiles and textures when they overlap or cluster in the same space, generating, perhaps, a more complex affective response. The texture of glyph-forms, which our studies have demonstrated plays a role in individual affect, may also have an impact on the emergent affect of complex visualizations. Figure 9 shows more densely-textured glyph-forms in the right column. Do the textures of individual glyph-forms mutually intensify, thereby increasing the affect produced by the individual forms? Or, in contrast, do the forms' textures mitigate each other, muting the cumulative impact?

This issue becomes even more complex when we consider multivariate volumetric data, as shown in Figure 10. Though affect may be significantly more difficult to test in this scenario—combinations of glyph-forms with varying affects may produce drastically different results than singular glyph mappings, and color appreciably impacts perception, affect, and association—this methodology also provides considerable value to visualizations of highly complex datasets by increasing intra-variate discrimination and communicative potential. Teasing apart and testing the many factors at play here will require the development of new testing methods, perhaps based in part on artistic design theory principles [51] that consider composition-level color, form, and texture interactions.

Another primary limitation of this work is the finite range of our testing groups. Though we made an effort to diversify by background and area of study, accounting for the breadth and variety of meaning in shapes and forms in cultural contexts outside the United States was beyond the scope of this paper. Does affect translate across geographic and linguistic bounds? Can we locate precise and consistent similarities and differences across cultural backgrounds? Investigating these and many more related questions is essential to this work, and we plan to pursue such avenues in the future.

9 Future Work

Though preliminary and exploratory, this work has opened the door to considerable future investigations of shape, materiality, association, color, holistic design analysis, and methodology approaches. In order to reduce variability and confounding inputs in our study, we limited our glyph-form material to clay. However, the materiality of objects in the world carry extensive implicit information, communicating not only the tangible quality, origins, and utilitarian intent of the objects, but also affective, emotional, and associative properties. Expanding our material input range would significantly expand affective and communicative potential. Further future work may include an investigation of the range of associative vs. abstract properties carried by our handmade forms. At what point does a form become more abstract than anthropomorphic? Is there a middle ground most effective for conveying the properties of an encoded variable without producing an overly-representational, and therefore too complex and too specific, glyph form for scientific visualization? Additionally, as discussed in Design Challenges, color is a primary and significant encoding channel for scientific visualization. How does color impact the affective qualities of handmade glyph-forms? (See Figure 10) Further considerations include employing a balanced design methodology to encode multivariate data with a diversity of glyph-forms carrying a range of profile complexities, densities of texture, curvatures, angularities, and sizes to reduce cognitive load and improve intuitive interpretation and aesthetic intrigue.

In terms of study methodology, these exploratory results point to several future iterations that could consider these new avenues of investigation. We chose to test images of three-dimensional forms rather than the forms themselves in order to avoid the confounding variables such as materiality, size, and weight. In future work, we plan to test the forms themselves, and to increase the range of materiality, size, and weight of these forms. This work may also be improved by a greater range of participants and a specific focus on art students or participants with arts backgrounds. Artists are trained to develop complex, high-level relationships with objects and their form-qualities in order to produce effective work. Participants with arts backgrounds may therefore react differently or provide new insights into the glyph-forms tested. Further future work will include an expansion of coding fidelity of the study data. Each glyph image was placed along two axes, though an analysis of their placement position beyond quadrants was beyond the scope of this paper. Deeper analysis may reveal interesting trends that could provide more insight on the relationship between form-qualities and affect for three-dimensional, handmade objects.

10 Conclusion

While much work remains to understand the role of affect in scientific visualization, this preliminary paper has illuminated several new and exciting avenues for future research. As the sciences become increasingly interdisciplinary, we are seeing more coupled model simulation output describing the chaotic, intricate, and interdependent processes that comprise our planet and our universe. In order to keep pace with these advancements in data production and analysis, visualization practitioners must also draw from adjacent disciplines, mingling art and design with computation, and bringing together the material and the digital in order to expand visual encoding schemes and communicative and analytical potential. Here, we have explored one such avenue of this mingling, by considering affect through artistic design.

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