A Survey of Natural Design for Interaction

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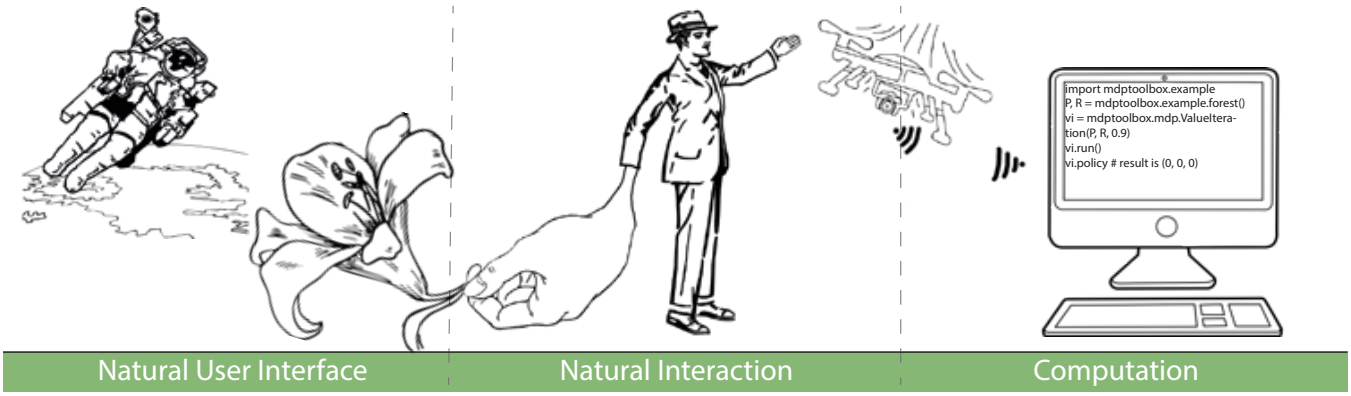

Figure 1: Three application examples for Natural Design in HCI: left) to create nature-inspired and familiar interfaces for living areas in space [65], middle) to enable natural interaction with drones [7] and right) to implement natural system behavior [72].

ABSTRACT

The term "Natural Design" has various meanings and applications within and beyond the human-computer interaction community. Yet, there is no consensus on whether it is a relevant design approach or only a descriptive term without profound meaning. We investigated the current understanding and design potential of "Natural Design" for interaction in a systematic literature review. By analyzing and rating 113 papers, we identified 47 relevant papers that applied Natural Design in different contexts. The understanding of the approach changes from nature-related inspirations to context-dependent naturalness based on increasing familiarity or expectations. We present a structured overview of these relevant papers, contribute a systematic Natural Design model for interaction and add 20 implications for applying Natural Design to natural user interfaces, natural interaction, or computation. We identified "Natural Design" as a relevant design approach to create intuitive and embedded interfaces that can profit from related concepts outside human-computer interaction.

CCS CONCEPTS

• **Human-centered computing → Interaction design theory, concepts and paradigms**.

MuC '22, September 4–7, 2022, Darmstadt, Germany

ACM ISBN 978-1-4503-9690-5/22/09…$15.00
https://doi.org/10.1145/3543758.3543773

KEYWORDS

Natural Design, Natural Interaction, Design Approach, Nature-Inspired, Context, Familiarity

ACM Reference Format:
Linda Hirsch, Jingyi Li, Sven Mayer, and Andreas Butz. 2022. A Survey of Natural Design for Interaction. In *Mensch und Computer 2022 (MuC '22), September 4–7, 2022, Darmstadt, Germany*. ACM, New York, NY, USA, 15 pages. https://doi.org/10.1145/3543758.3543773

1 INTRODUCTION

The term "Natural Design" mainly denotes approaches for designing with and for nature in various contexts. For example (see Figure 1), it is used to design comfortable and recreational space habitats for astronauts [75], and also used when designing new human-drone interactions [7]. On the other hand, in fields outside of human-computer interaction (HCI), such as philosophical behaviorism [84] or bioengineering [8], Natural Design is an established terminology. However, each field has an individual purpose for using it as the definitions differ across them. For example, bioengineering transfers biological mechanisms and processes into Natural Designs, thereby creating nature-inspired, artificial systems [8]. Thus, it is only natural that an interdisciplinary community, such as the HCI community, will pick up such a term from different fields and use it with various meanings and application areas without a common shared understanding. It is even debated whether Natural Design is a relevant approach in interaction design or just a term that explains the features of a target system.

We argue a clear understanding and definition of the term is needed to communicate and collaborate within and outside our community [36]. In addition, HCI often works at the intersection with other disciplines, which creates the challenge of generating a

common language and understanding among stakeholders [21]. Furthermore, Natural Design has been shown to support the creation of intuitive and embedded interfaces [7, 39, 41]. However, Natural Design currently lacks a structured definition and overview of design implications to apply it easily, e.g., the creation of natural user interfaces (NUI) or embedding interfaces unobtrusively into different public environments. Illustrating the term's meanings and applications within our community supports identifying the potential and limitations of the Natural Design approach for future projects. We aim at contributing an understanding of what Natural Design is in relation to NUIs and natural interaction for different realities and environments and how it can be implemented. From these observations, we derive the following research questions:

RQ1 What is the current, shared understanding of Natural Design for interaction within HCI?
RQ2 How can HCI researchers and practitioners apply it?
RQ3 What distinguishes HCI Natural Design from other fields' approaches outside HCI?

We investigate the current understanding of Natural Design in the HCI community by conducting a systematic literature study in the ACM Digital Library by applying the Preferred Reporting Items for Systematic Reviews (PRISMA) [49] procedure for our analysis. In total, we extracted 113 conference and journal papers, in which the term was mentioned at least once in the main body or abstract. Based on them, we clustered how HCI researchers are using the term regarding its definitions, intentions, properties, and modalities across multifaceted study contexts resulting in n=47 papers overall. The complete data sample can further be explored in our web tool[1].

Our work identified three main application areas of Natural Design within HCI, natural user interfaces, natural interaction, and computation. We contribute 20 implications to apply Natural Design for a context, human, or system. Those can be used to arrive at either a context-dependent natural system or interaction behavior that further allows for seamlessly embedded interfaces and intuitive interaction. Our results also show that the understanding of Natural Design ranges from nature-related inspirations to context-dependent naturalness based on increasing familiarity. Approaching this versatile understanding, our work provides a systematic Natural Design for the interaction model, which aims at enabling others to increase their common understanding and communication, see Figure 5. We identified Natural Design as a relevant design approach in general with the potential to seamlessly embed interfaces into different types of environments while keeping them recognizable to the users. Moreover, the various definitions we identified align with the established approaches outside our community [8, 70, 86, 91], which could in turn also benefit from our implications and the more user-centered perspective.

2 RELATED WORK

Natural Design is a much-discussed term in other research fields, such as philosophical behaviorism and sustainable design. We briefly introduce related approaches outside and within HCI.

2.1 Natural Design Outside HCI

Philosophical behaviorism uses the Natural Design of animal behaviors to explain human behaviors [84] by conveying findings from the similar yet simplified natural animal behavior. One of the main claims is that any design is based on a certain intention, which can be interpreted based on former known behavioral patterns and knowledge [85, 86]. *Sustainable design* focuses on a holistic perspective that contributes to sustaining beyond-the-human environments. This means it adapts interfaces to the respective natural context by copying nature-inspired designs and mechanisms [9, 45, 54, 89, 91]. It comprises designing for human psychological and physical well-being [3], the socio-cultural settings of a target environment [87] and biological nature conditions. The latter includes *biophilic* and *biomimicry* approaches, whereas biophilic design aims to evolve the human-nature relationships by integrating nature-inspired characteristics and artefacts (e.g. eco-friendly architecture[2]). In contrast, *biomimicry* is an umbrella term for nature-inspired designs, and design approaches, widely used in bioengineering [8, 9, 89]. For example, the lotus effect, which describes the effect of water and dirt repelling surfaces [54], fosters material and technological innovations and influences the design of everyday objects like self-cleaning glass facades.

2.2 Natural Interaction

Within HCI, *natural interaction* is a prominent and widely understood term that is related to Natural Design, yet mainly used independently. Aiming for intuitive, non-intrusive interactions [4], it emphasizes the content rather than the interaction itself. Additional characteristics are the execution of an interaction in real-time [58, 99] and under real-spatial [13, 24] conditions. Compared to other interaction designs, natural interaction design considers user emotions and emotional cues in communication as well [13, 92]. Kerne et al. [46] extend the emotional communication level by including the user's cultural background in the design of natural interaction. Thereby, they exploit the user's embodied mental models of objects and their related interactions for the natural user interface design process. Prior work also discusses the limitations of natural interaction. Norman [62], for example, refers to a virtual bowling game on the Nintendo Wii console, in which users tended to let loose of their controllers with high force in the heat of the game, partly destroying their inventory. Galais et al. [27] report that users performed faster and with less cognitive effort using the VR controllers' buttons than with natural gesture interaction. The current research on natural interaction shows a gap of lacking criteria and guidelines to decide when it should be considered in the design process.

2.3 Natural User Interfaces

NUIs are often mentioned in combination with natural interaction [16, 17, 33, 47]. They serve as the medium enabling interaction and behaviors natural from a user perspective [94]. Common characteristics of such interfaces, among other details, are the 3D shape

[1]Please check out our web tool https://ndevolution.github.io/natural-design/ providing an interactive data visualization tool with all 113 references and their ratings.

[2]https://www.architecturaldigest.com/story/how-milans-bosco-verticale-has-changed-the-way-designers-think-about-sustainable-design, last accessed Jan. 31st 2022

and its physical and spatial positioning in the environment. Previous research also relates a NUI to materiality, especially in the context of tangible interaction [76]. Others emphasize the quality of a NUI to disappear in its functional purpose through the easy and seamless engagement of the user with the content [19, 50]. The term is mostly used in the context of gesture interaction [36, 47, 62], but can also be applied for any interface allowing a direct interaction demanding little attention capacities and requiring little learning effort in general [17, 79]. At the same time, a natural interface needs to be well-adapted to and well-embedded in its surroundings. A common strategy to design NUIs is to make use of prior user knowledge and to apply familiar concepts from "the real world" to the interface [33, 79, 90], thereby drawing on the user's mental model to facilitate the user's process of meaning-making [90].

2.4 Summary

Natural Design outside HCI, natural interaction, and NUIs always seem to relate to either biological nature or context-specific human nature. However, the perspectives differ significantly. Setting Natural Interaction, Natural Design, and NUIs in relation to each other, we see Natural Design as a holistic design approach, including concepts and guidelines to create NUIs and natural interactions. Yet, it lacks an overview of its definitions to enable shared and clear understanding in delimitation to NUI and natural interaction. Additionally, a structured collection of design implications is missing that would support designers in how to approach Natural Design in interaction and for what contexts.

3 METHODOLOGY: CONDUCTING A SYSTEMATIC LITERATURE REVIEW

To work toward a holistic understanding of Natural Design in the context of interactions, we conducted a systematic literature review for the search term *Natural Design*. We used the term *"Natural Design"* as one single keyword to apply the PRISMA [49] procedure including the PRISMA protocol[3]. Our initial selection included any published format containing our search term resulting in 192 hits at data collection time (May 2021). Figure 2 shows our iterative screening process and includes additional details, such as our rating criteria and our review validation approach. Below, we will explain it step by step.

3.1 Phase I: Identification

In the *identification* phase we searched the ACM Digital Library (ACM DL) for papers containing the term *Natural Design*. In HCI, the ACM DL is the most relevant source for interaction papers. Therefore, we limited our search to the ACM DL, and thus, only focused on the relevant literature in the context of interactions. Overall, we exported a total of 192 references in which the term *Natural Design* occurred.

3.2 Phase II: Screening

Focusing our data on conference and journal papers only, we excluded all posters, workshop papers, works-in-progress, etc. Moreover, we removed two TOCHI journal papers, [32, 57] from the set that extended their original papers but did not include any updates on their definition of Natural Design. Therefore, we kept the earlier papers instead [31, 56]. We excluded duplicates and papers in which the term did not appear in the full text, resulting in 113 references.

[3]http://prisma-statement.org/documents/PRISMA-P-checklist.pdf, last accessed June 8th, 2022

3.3 Phase III: Eligibility

In the *eligibility* phase, we conducted an in-depth manual content assessment by analyzing the semantic context of the paragraphs in which our search term appeared. For this, we identified three main categories based on the initial scouting of the papers: their definition, intention, modalities, and characteristics of applying Natural Design. The *Definition* of Natural Design helped us understand how prior work specified the term. Next, we looked at the *Intentions* to apply Natural Design and if it was applied as a design approach or as a descriptive term only. The last category looks at natural design-related *Modalities & Properties*. We related modalities to interaction modalities and properties to other attributes that refine the definition. Organizing our results according to their thematic focus on Natural Design (applying the conceptual organization by Domino et al. [20]), we used these categories to rate the papers' relevance.

Two authors iteratively scored 50% of the 113 references each based on these three categories during the first full reading round. We defined a scoring scheme (5-point scale) to rate the papers on which we based our exclusion. This first iteration included a control review by exchanging and scoring ten papers (10% of each data set) from the other half to ensure inter-rater reliability. We used the approach by Campbell et al. [11] comparing each coder's scores per category and the overall score. The coding showed an intercoder agreement of 90%. The remaining disagreements on the categorization resulted mainly from different assessments of the papers' focus, particularly whether the definition of Natural Design was extensive and explicit enough to include it in our literature set. Cleaning these inconsistencies, we refined our rating scheme for the three categories and re-rated the papers.

3.4 Phase IV: Included Data Sample and Processing

We included all papers rated ≥ 4 for Definition (n=10) and Intention (n=27) for our final data set. However, for Property & Modality, we found it insightful to include papers that scored ≥ 3 (n=46) because most papers focused on either properties or modalities, and the overlaps would have been minimal otherwise. Any papers below these ratings were excluded from further analysis. Lastly, we compared reoccurring elements for each category to identify common clusters and grouped uniquely appearing characteristics under "miscellaneous." We list all further included papers (n=47) in Table 1.

4 RESULTS

In this section, we first summarize the general findings as presented in Figure 3, including all 113 analyzed papers. Subsequently, we decided to focus on delivering the results based on the most relevant papers per category only using the central coverage approach as shown in Domino et al. [20].

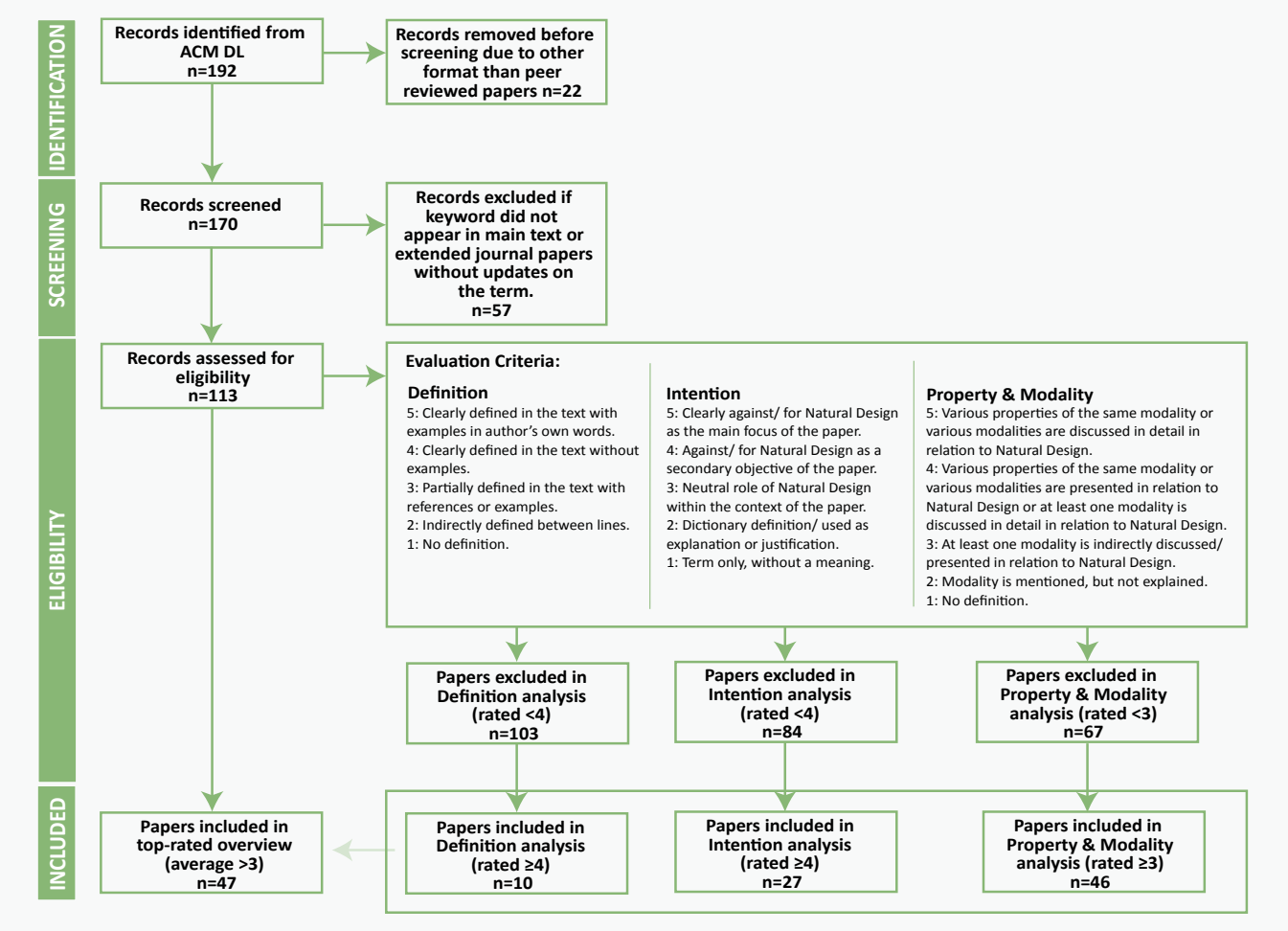

Figure 2: Systematic literature study using the PRISMA: The review was executed by two authors and consisted of four phases: identification (n=192), screening (n=170), eligibility (n=113) and inclusion (n=47). Of those 47, we included n=10 in the Definition cluster; n=29 in the Intention cluster; and n=46 in the Property & Modality cluster (counting n=23 in modalities and n=43 properties).

4.1 Natural Design Appears Most in the ACM CCS Software and its Engineering

After cleaning our data, we calculated the papers' distribution by publication year and CCS classification. The distribution in Figure 4 shows the strongest representation of Natural Design in Software and its Engineering with a total of 21 papers. This category also introduced the term in 1979 in Saal and Weiss's work about the design of an APL interpreter [71]. In comparison, the first paper from the Human-centered Computing cluster, including *Natural Design* appeared in 1991 in work by MacLean et al. [52] about the role of analogies in user interfaces. Considering the total number of occurrences, Figure 4 shows an increasing trend of Natural Design since 1999. In contrast, according to our coding, the first clear definition appeared in 2004 in Santana et al.'s paper about the programming of artificial intelligent agents [72].

4.2 The Main Common Definition Relates To Familiarity

Altogether, ten papers scored ≥ 4 in terms of definition. By dissecting these ten papers, we derived four definition clusters of Natural Design: 1) *Inherent or Acquired Familiarity*, 2) *Recreation of Nature*, 3) *Expected Design Choice or Alternatives*, and 4) *Expected Design Principle or Strategy*.

4.2.1 Inherent or Acquired Familiarity. We found that the main consensus on Natural Design's definition is: *Inherent or Acquired Familiarity* (n=4) [7, 10, 40, 41]. However, the results suggest familiarity here is threefold: First, in terms of User Interfaces (UIs), Natural Design refers to the inherent familiarity with deformability rooted in natural, living organisms [41] and material [40]. Applying this approach means adapting UIs' shape and appearance to surrounding conditions to increase affordance and accessibility. Second, regarding intuitive control via interaction, Natural Design

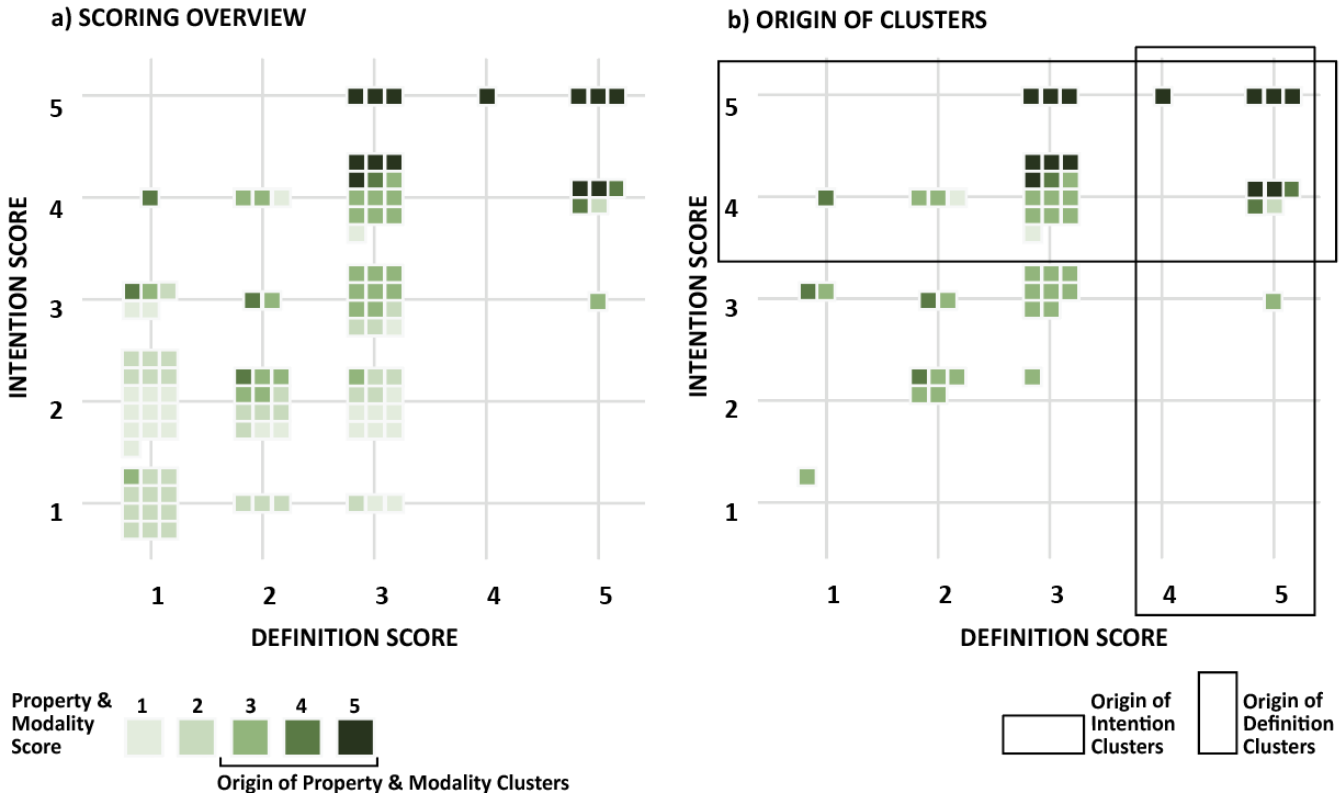

Figure 3: Rating overview: We selected 113 papers from which we deduced three categories for analysis, *Definition*, *Intention* and *Property and Modality* (a); resulting clusters for Definition (≥ 4, n=10), Intention (≥ 4, n=27), and Property and Modality (≥ 3, n=46) (b) Highlighted top-rated papers.

indicates already embodied habits in human beings toward contact with other living beings, such as pets. Those habits are based on both inherent and acquired familiarity [7]. They serve as a natural design metaphor for interaction, aiming to foster an intuitive control with computers. Third, with regards to interaction modalities, Natural Design highlights the bodily acquired familiarity in movements used for a task in daily life [10, 40]. Thus, it designs interaction techniques with as many modalities that correspond to real-world actions as possible.

4.2.2 Recreation of Nature. In comparison, we consolidated others' definition under *Recreation of Nature* (n=2) [65, 75]. Both papers focus on designing new environments, namely space shuttles and stations. By recalling earthly related physical and psychological conditions, authors tried to foster mental and physical well-being, orientation, and support for human activities in space habitats [75].

4.2.3 Expected Design Choice or Alternatives. Moreover, authors commonly use "natural" as the adjective describing a design as "normal" or "expected" within a project (n=2) [60, 72]. We summarized it under the cluster *Expected Design Choices or Alternatives*, which focuses on typical or expected single design choices or multiple alternatives to a specific practical problem, mainly in software systems. For example, in the most straightforward single-agent patrolling task, an expected design choice is to achieve efficient navigation between adjacent nodes with limited steps of action [72]. In an on-demand catch-up TV service, expected design variants were generated by using different optimization functions or predictors yielding different weighting factors [60].

4.2.4 Expected Design Principle or Strategy. Similarly, the *Expected Design Principle or Strategy* cluster (n=3) [31, 37, 63] emphasizes a normal or expected design principle or strategy to a general theoretical question in a relevant research context. For example, in the theory of computation, a natural design principle of algorithmic mechanisms is to prefer the remaining items with higher value-per-cost ratios than the ones with lower ratios [31]. Another example in HCI, the principle of natural design decision making, is characterized by a design decision formed through an iterative process, made rapidly under time pressure, and captured during an information-seeking process [37].

4.2.5 Overall. We derived four Natural Design definitions. Two mainly relate to a computation-centered perspective (*Expected Design Choice or Alternatives* and *Expected Design Principle or Strategy*). *Inherent or Acquired Familiarity* is strongest discussed in the context of natural interaction and the design of NUIs. In contrast, we found the *Recreation of Nature* definition only considering NUIs design in dependence of their application environment.

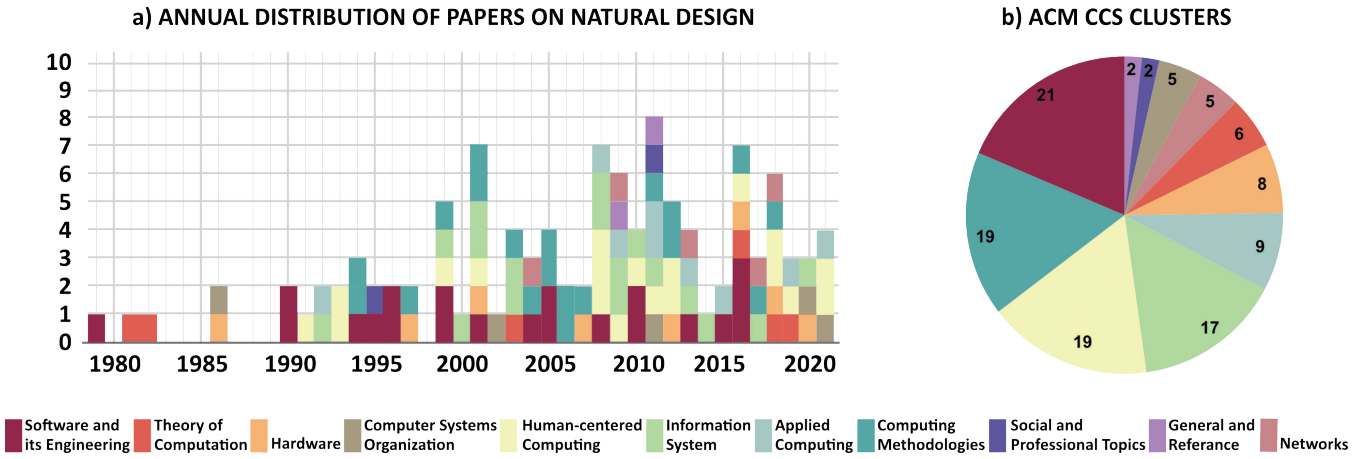

Figure 4: Natural Design in ACM CCS: Distribution of number of papers on Natural Design acc. to publication year and ACM CCS.

4.3 Increasing Usability Is The Main Intention To Apply Natural Design

We identified 27 papers in the intention category (papers scoring ≥ 4). The majority (n=19) discussed Natural Design with the intention of designing for usability. In contrast to the definition category, we allowed more than one intention cluster per reference if applicable. We found six different intention clusters in total: 1) *Designing for Usability*, 2) *Normality*, 3) *Criticism*, 4) *Realistic Design*, 5) *Designing for Well-being*, and 6) *Inspiration from Nature*.

4.3.1 Designing for Usability. In the cluster *Designing for Usability*, Natural Design is mainly applied to increase the usability of a system, such as [55, 61, 63, 73, 81, 96], to create intuitive user interfaces [7, 15, 38, 40, 43, 44], and to increase the understandability of a system [93]. Interfaces derived from a natural design approach are called intuitive if they are controlled via natural user interactions [38, 60, 61, 81], such as gesture, voice, or touch. Intuitive UIs are based on the acquired familiarity when a simple and natural dialogue closely matches the user's task organization [61]. Another example is the application of auditory icons perceived as familiar through users' lifelong learning processes and general familiarity with voice and sound interactions [43, 44]. In comparison, authors focusing on the understandability of an interface discussed familiar visual patterns in their design process, which serve as a common language basis [1, 40].

4.3.2 Normality. Another intention cluster is based on the intention of copying or creating a *Normality*. Here, we found that the authors of our reference papers [40, 72, 75, 81, 93, 95] argued for human behavior to be normal when users had formed a habit out of an activity or out of a situation that is regularly performed [72, 81, 93] or related to certain contexts [40, 75]. It includes the intention of influencing certain user behaviors toward new behavioral patterns through nudging [95], such as fostering sustainable behavior by taking the bicycle instead of the car. In contrast, normal system behavior is an implemented, reoccurring reaction or communication pattern that is considered normal or expected from a system [2, 30, 31, 48, 100]. Thus, researchers transferred human behavior patterns onto agents to facilitate natural communication that would require little learning effort from the user [7, 72]. Moreover, the Natural Design in multi-user communication is based on the activities and gestures that are normally a part of face-to-face interaction between multiple parties. Therefore, it can foster both usability and normality, of remote collaborative interaction [93].

4.3.3 Criticism. In the cluster *Criticism*, researchers argue against or mention problems by using Natural Designs [2, 10, 40]. For example, keeping a conventional algorithmic design in data mining also means keeping the same problems as before [2]. Besides, Hirsch et al. [40] compared a "Traces-of-Use-inspired design strategy" versus clean and clear shapes for tangible concrete interfaces. They reported that the irregular used-look invited participants to explore but were also harder to understand and to keep control. Thus, the criticism addresses the flaws and limitations caused by considering realistic and familiar conditions [10, 40]. Instead, the opportunities provided by dynamic digital interfaces are ignored and not exploited to their full potential.

4.3.4 Realistic Design. *Realistic Design* represents references considering spatial conditions, 3D shapes and external, physical conditions [40, 73, 88, 96]. As an example, Umetani et al. [88] created a tool to support garment design. To create an appealing look and cut, it is essential to consider the draping and shaping of the garment in movement and gravity and how these external, physical forces affect the design's look. It further reveals the need to simulate real-world conditions and forces in digital design tools, particularly if the design's application area is the real environment.

4.3.5 Designing for Well-being. The cluster *Designing for Well-being* means applying a nature-inspired design approach [41, 65, 75]. This includes the usage of patterns and shapes occurring in nature, such as flowers or different types of greens [65, 75]. Another nature-inspired quality is further found in organic user interfaces, which change shapes and convey a certain autonomy or liveliness onto an interface [41]. In comparison to the *Inspiration from Nature*, this

cluster avoids imperfections or realistic limitations but focuses on the aesthetics and beauty of nature.

4.3.6 Inspiration from Nature. Lastly, the *Inspiration from Nature* cluster comprises nature or organic systems that serve as inspiration for a system design [65, 82] or as discussion basis [10, 41]. For example, Holman and Vertegaal [41] presented in their work the advantage of organic, deformable, and shape-changing interfaces to increase affordance and information richness. They also related Natural Design to wabi-sabi, a Japanese design philosophy, which embraces "natural imperfections and impermanence." In contrast, Ono and Schlacht [65] applied Natural Design to create outer space environments with the argument that it would foster psychological well-being.

4.3.7 Overall. Our results identified six Intention clusters: 1)*Designing for Usability*, 2) *Normality*, 3) *Criticism*, 4) *Realistic Design*, 5) *Designing for Well-being*, and 6) *Inspiration from Nature*. The first four appeared widely in natural system design, NUIs or natural interaction. In comparison, the last two considering *Designing for Well-being* and *Inspiration from Nature* only presented Natural Design in the context of NUI [65] or the design of environments [75].

4.4 Most Literature Focused on Either Properties or Modalities

In total, we identified 46 references mentioning properties and modalities related to Natural Design. We decided to present properties and modalities separately while they are rated in one score together. This is because some papers either mentioned only properties or modalities. In our context, modalities relate to interaction modalities, while properties relate to design characteristics.

4.4.1 Properties of Natural Design. There are two main properties related to Natural Design. First, a "natural" property indicates the easiness of an activity (n=14). Our findings are summarized in the *Ease* cluster in Table 1. It comprises the properties easy-to-learn [25, 43, 44, 51, 88, 93], easy-to-use [15, 40, 78, 81], easy-to-access [73], easy-to-recognize [1], and easy-to-offload [60]. Second, researchers (n=13) argue for the importance of *3D Shapes* or interactions in a Natural Design. In eight of these cases, researchers apply 3D shapes in AR or VR to achieve a more natural user experience [15, 48, 73, 78, 88] or for a facilitated collaboration and user understanding in the real environment [15, 22, 23]. Additionally, Bowman et al. [10] and others [25, 51] show the benefit of enabling 3D interaction techniques on a 2D screen interface. In Bowman et al.'s study [10], participants interacted with a virtual object through hand trackers (the more natural choice) and mouse and keyboard (less natural). The more natural interaction increased the fidelity and hence, "outperformed" the less natural alternative. In comparison, in Mackinley et al.'s study [51], users interacted with 3D digital information on a 2D screen. While dealing with occlusion, their results confirm their users' increased "intuitiveness" due to the 3D shape. In Yang and de Veciana [98] and Omicini and Zambonelli [64], authors talk about spatial features and properties supporting the implementation to reflect interactions and user behavior in the code or system communication. Others relate shapes to 2D visual modalities, pattern recognition, and the usage of nature-inspired shapes [40, 65, 75]. *Patterns*, such as consistent, hierarchical data structures in a computational context [68] or familiar and repetitive floral shapes [65], are another feature of Natural Design. The same accounts for spatial behavior, including *Spatial Position* and artifacts' relations in 3D space. This includes aspects, such as occlusion, shadowing, or positioning [1, 23, 48, 64, 73, 78, 96], which are in close relation to the effects mentioned above of 3D shapes. Several authors [64, 73, 75, 98] consider a system-driven activity in which the system or the agent changes, reacts, or is otherwise autonomously active as a natural design property. It resembles something being alive [41] or organic [40] in the *Inspiration* intention cluster. Regarding processes and collaboration tools, the simulation of scenarios or data flows was also classified as Natural Design [15, 53, 82] due to being a familiar way of sharing and communicating information. Lastly, we also identified various uniquely appearing properties that described the Natural Design of a system [2, 14, 25, 26, 28, 30, 31, 34, 35, 55, 63, 66, 69, 72, 74, 82, 97], such as applying a hierarchical system design [28] or aiming for reusable and incremental classes [14].

4.4.2 Overall Properties. We found Natural Design properties equally distributed regarding NUI design and natural interaction. Yet, we could barely find common properties in computation contexts, where the properties were primarily system-specific and unique.

4.4.3 Natural Design Modalities. The interaction modality mentioned most is *Tangible* and *Tactile* interaction, e.g., [10, 18, 40, 48, 69, 78, 93]. Various papers target sketching as a tangible interaction modality in particular. With this, researchers looked at natural either by providing 2D sketching tools for 3D visualizations [73, 96] or by augmenting sketches by considering "natural conditions", such as gravity [88]. It is closely followed by *Auditory*, *Voice*, *Visual*, and *Manipulating* interactions. The latter point is split into an active conscious manipulation by the user [88, 93, 96] and passive subconscious manipulation of the user, and their behaviors by a third person, a system [95] or design [40]. *Visual* interaction is, for example, mentioned concerning pattern recognition, which is further called pleasing for the eye [61, 65, 75]. In comparison, *Auditory* modality was either discussed in the design of soft body sounds [81] or in combination with *Voice* modalities. In the latter, Jeon and Walker [43] and Jeon et al. [44] present the idea of auditory menu navigation on the smartphone via speech input and auditory output. The idea is in both references based on the "natural mapping" of sound or speech to object or icon recognition. Due to a daily and lifelong usage of one's voice. This description resembles the *Inherent or Acquired Familiarity* with the definition cluster. Su and Joslin [81] further present their approach about rendering realistic, or natural, auditory cues for soft bodies and the remaining difficulties to deal with the noisy sound they emit. Instead, Baytas et al. [7] discuss voice interaction in the context of agent interaction, whereas Weibel et al. [93] apply it as a natural collaboration modality.

Researchers also aimed to identify and apply natural or as close to natural *Gestures* as possible in their design. Yet, the approach of identifying natural gestures differs. While Baytas et al. [7] relate properties, such as embodied and ergonomic interaction, Rusnák et al. [69] apply "well-known" gestures, such as slide, pinch, or turn. Lastly, four references also implied a Natural Design by not having an interaction but automatic system activities [18, 53, 68, 81].

Table 1: We included 47 papers resulting in Definition, ≥ 4, n=10 papers, Intention ≥ 4, n=27, and Property and Modality, ≥ 3, n=46.

		Definitions				Intentions						Properties							Modalities							
	References	Familiarity	Recreation	EDCA*	EDPS**	Usability	Normality	Criticism	Reality	Well-being	Inspiration	Ease	3D Shape	Pattern	Spatial Position	Alive/Organic	Simulation	Misc.***	Tangible/Tactile	Auditory	Visual	Manipulation	Voice	Gestures	Automatic System
NUI	Holman and Vertegaal [41]	●	-	-	-	●	-	-	-	●	●	-	-	●	●	-	-	-	-	-	-	-	-	-	-	-
	Ono and Schlacht [65]	-	●	-	-	-	●	-	-	●	●	-	●	-	-	●	-	-	●	●	●	-	-	-	-	-
	Bowman et al. [10]	●	-	-	-	●	-	●	●	-	●	●	●	-	●	-	-	-	●	-	-	●	●	-	-	-
	Hirsch et al. [40]	●	-	-	-	●	●	●	●	-	-	●	●	●	-	●	-	-	●	-	●	●	-	-	-	-
	Schlacht and Birke [75]	-	●	-	-	-	●	-	-	●	●	-	●	-	●	●	-	-	-	●	-	-	-	-	-	-
	Nielsen [61]	●	-	-	-	●	-	-	●	-	-	-	-	●	-	-	-	-	-	-	●	-	-	-	-	-
	Hindriks and Jonker [38]	●	-	-	-	●	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Abraham and Atwood [1]	-	-	-	●	●	-	●	-	-	-	●	-	●	●	-	-	-	-	-	-	-	-	-	-	-
	Ogawa et al. [63]	-	-	-	●	●	-	-	-	-	-	●	●	-	-	-	-	-	-	-	-	-	-	-	-	-
	Mackinlay et al. [51]	-	-	-	●	●	-	-	-	-	-	●	●	-	-	-	-	-	-	-	●	-	-	-	-	-
Natural Interaction	Baytas et al. [7]	●	-	-	-	●	●	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	●	●	-	-
	Sareika and Schmalstieg [73]	●	-	-	-	●	-	-	●	-	-	●	●	-	●	●	-	-	●	-	●	●	-	-	-	-
	Weibel et al. [93]	●	-	-	-	●	●	-	●	-	-	●	-	-	-	-	-	-	●	-	●	●	-	●	-	-
	Umetani et al. [88]	●	-	-	-	●	●	-	●	-	-	●	●	-	●	-	-	-	●	-	●	●	-	-	-	-
	Xin et al. [96]	●	-	-	-	●	-	-	●	-	-	●	●	-	●	-	-	-	●	-	●	●	-	-	-	-
	Jeon and Walker [43]	●	-	-	-	●	-	-	●	-	-	●	-	-	-	-	-	-	-	●	●	-	-	●	-	-
	Jeon et al. [44]	●	-	-	-	●	-	-	-	-	-	●	-	-	-	-	-	-	●	●	●	-	-	●	-	-
	Winkel et al. [95]	-	-	-	●	-	●	-	-	-	-	-	-	-	●	-	-	-	-	-	-	●	-	-	-	-
	Liang et al. [48]	●	-	-	-	-	-	-	●	-	-	-	●	-	●	-	-	-	●	-	-	-	-	-	-	-
	Dodds [18]	-	-	-	●	●	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	●
	Simon et al. [78]	●	-	-	-	-	-	-	●	-	-	●	●	-	●	-	-	-	●	-	-	-	-	-	-	-
	Rusnák et al. [69]	●	-	-	-	●	-	-	-	-	-	-	-	-	-	-	-	●	●	-	●	-	-	●	-	-
	Dachille et al. [15]	●	-	-	-	-	-	-	●	-	-	●	●	-	-	-	●	-	●	-	-	-	-	-	-	-
Computation	Santana et al. [72]	-	-	●	-	-	●	-	●	-	-	-	-	-	-	-	-	●	-	-	-	-	-	-	-	-
	Gravin et al. [31]	-	-	-	●	●	●	-	-	-	-	-	-	-	-	-	-	●	-	-	-	-	-	-	-	-
	Hayes and Akhavi [37]	-	-	-	●	-	-	-	●	-	-	-	-	-	●	-	-	-	-	-	-	-	-	-	-	-
	Nencioni et al. [60]	-	-	●	-	●	-	-	-	-	-	●	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Mckelvey and Agrawal [55]	-	-	-	●	●	-	-	-	-	-	-	-	-	-	-	-	●	-	-	-	-	-	-	-	-
	Gockenbach et al. [30]	-	-	●	-	-	●	-	-	-	-	-	-	-	-	-	-	●	-	-	-	-	-	-	-	-
	Agarwal et al. [2]	-	-	-	●	-	●	●	-	-	-	-	-	-	-	-	-	●	-	-	-	-	-	-	-	-
	Su and Joslin [81]	●	-	-	-	-	●	-	-	-	-	●	-	-	-	-	-	-	-	●	-	-	-	-	-	●
	Subbaraman [82]	●	-	-	-	-	-	-	●	-	●	-	-	-	-	-	●	●	-	-	-	-	-	-	-	-
	Passarella et al. [68]	●	-	-	-	-	●	-	●	-	-	-	-	●	-	-	-	-	-	-	-	-	-	-	-	●
	Geirhofer et al. [28]	-	-	●	-	-	●	-	-	-	-	-	-	-	-	-	-	●	-	-	-	-	-	-	-	-
	Du and Qin [23]	●	-	-	-	●	-	-	●	-	-	-	●	-	●	-	-	-	-	-	-	-	-	-	-	-
	Yang and de Veciana [98]	-	-	●	-	●	-	-	-	-	-	-	-	-	-	●	-	-	-	-	-	-	-	-	-	-
	Du [22]	●	-	-	-	●	-	-	●	-	-	-	●	-	●	-	-	-	-	-	-	-	-	-	-	-
	Omicini and Zambonelli [64]	-	-	●	-	●	-	-	-	-	-	-	-	-	-	●	-	-	-	-	-	-	-	-	-	-
	Xu et al. [97]	-	-	●	-	-	●	-	-	-	-	-	-	-	-	-	-	●	-	-	-	-	-	-	-	-
	Gafni [25]	-	-	-	●	●	-	-	●	-	-	●	-	-	-	-	-	●	-	-	-	-	-	-	-	-
	Manivannan et al. [53]	●	-	-	-	●	-	-	●	-	-	-	-	-	-	-	●	-	-	-	-	-	-	-	-	-
	O'Toole and Shrira [66]	-	-	-	●	●	●	-	-	-	-	-	-	-	-	-	-	●	-	-	-	-	-	-	-	-
	Carré and Geib [14]	-	-	-	●	●	-	-	-	-	-	-	-	-	-	-	-	●	-	-	-	-	-	-	-	-
	Hammer and Mc Leod [35]	-	-	●	-	●	●	-	-	-	-	-	-	-	-	-	-	●	-	-	-	-	-	-	-	-
	Hammar et al. [34]	-	-	-	●	●	-	-	-	-	-	-	-	-	-	-	-	●	-	-	-	-	-	-	-	-
	Gajski [26]	-	-	-	●	-	●	-	-	-	-	-	-	-	-	-	-	●	-	-	-	-	-	-	-	-
	Schelfthout et al. [74]	-	-	●	-	●	-	-	-	-	-	-	-	-	-	-	-	●	-	-	-	-	-	-	-	-

1 2 3 4 5

*Expected Design Choice or Alternative **Expected Design Principle or Strategy

***Miscellaneous

4.4.4 Overall Modalities. Overall, the identified modalities are either related to the human's physiological abilities or cause changes in the appearance of, e.g., an interface. Natural Design modalities appeared mainly to natural interaction and NUIs but only little in the computational context.

4.5 Summary of Results

To summarize, we present all presented papers in Table 1. It includes all references ranking ≥ 4 in the Definition and Intentions cluster and ≥ 3 for Modalities and Properties. We grouped the papers according to their focus on Natural Design, whether they focused on natural user interface design, natural interaction, or considered it from a computation perspective. Additionally, we assigned each paper with outstanding scores to the corresponding definition, intention, property, and modality clusters.

5 SYSTEMATIC NATURAL DESIGN FOR INTERACTION MODEL AND DESIGN IMPLICATIONS

The results of our evaluation criteria revealed connections and dependencies among the clusters that we visualized in Figure 5, our systematic Natural Design for interaction model. It incorporates design implications to arrive at either a NUI, natural interaction or a naturally designed computational system. We further found that each of these application areas strongly links to a respective design subject, the artifact, person, or space that Natural Design is applied for. We call them the system, human, and context. The subjects and application areas are interconnected, as presented below. Additionally, the figure emphasizes the connection between the results per cluster and the derived design implication.

5.1 Systematic Natural Design for Interaction Model

Our systematic Natural Design for interaction model links application areas to design implications and subjects. Additionally, the data to environment range indicates the broadness of application areas that Natural Design can be and has been applied within HCI. It includes the varying perspectives and details the identified references reveal, from Natural Design data flows [98] to the Natural Design of space habitats [75].

The *Computation* layer applied the Natural Design to (re-)design a system to either make them more usable and understandable for programmers or to define and structure implementation styles and system architectures. Hence, the application context is computational-centered on this layer, focusing on the basic details and functionalities of a system and the system-specific natural properties. Accordingly, papers of this layer do not include any interaction modalities but rather cover unique, nonrecurring properties (cf. [2, 25, 34]). The primary purpose of applying a natural design approach or natural design criteria is to describe a normal system behavior or to implement common, established system structures, communication styles, etc.

The *Natural Interaction* layer comprises the selection of natural interaction modalities with which the user changes, manipulates, or communicates with the interface and the available content. The goal is to design for context-specific interactions or under contextual conditions to create a realistic, natural experience [7, 73, 88]. However, the main focus is to derive or apply interaction modalities that are easy-to-learn and -use to achieve better usability and enable intuitive interactions, cf. [73, 93].

The *NUI in Context* layer focuses on the representation and embeddedness of the interface in context. Here, we see the most influence of nature-inspired design choices on the interfaces' aesthetics, shaping, and positioning. The intention of applying Natural Design to create NUIs is mainly, but not only based on designing for well-being and recreation. This includes considerations about natural or familiar interaction modalities [65, 75] and aims at holistically creating connections between the interface, the underlying system, and the environment [41, 65, 75].

While each layer is presented individually, they are closely intertwined and can influence each other. Baytas et al. [7] present how the design of social agents is influenced by copying natural human-to-pet interactions, giving general design suggestions. Additionally, Subbaraman [82] explains the programming of artificial intelligence based on the human brain and its neural connections. Thus, a natural organism inspires the creation of an intelligent artifact. In addition to the impacts of natural interaction and NUI on the data layers in Figure 5, the natural system design choices influence and limit the range of perceived possible interactions. Depending on how the content is presented, the user is (sub-)consciously triggered by design to interact in a certain way. Winkel et al. [95] discuss the use of nudges as a natural means to influence user behaviors subconsciously and the ethical responsibility of designers applying nudges. However, while our literature review revealed examples for natural interaction and nature-inspired interfaces influencing the system design choices, there are no examples in which the naturally designed computational layer inspired natural interaction or NUIs in reverse.

5.2 Implications for Applying Natural Design

We derived 20 implications for applying Natural Design to interaction for the different application areas by analyzing our data considering our clusters. An overview is given in Figure 5, and we will discuss them grouped by cluster:

5.2.1 Definition Implications. The definitions include design implications when designing for a system, a user, and an environment. For the latter, we derive the main implications emphasizing the need to apply interfaces and test them under *N1:* real-world physical conditions [10, 75]. Similarly, *N2:* applying onsite re-occurring color-codes and materials [40, 41, 65] supports seamlessly embedding interfaces into an environment. Focusing on the user, Natural Design means enabling the user to interact in a new context or with new technology with usual, familiar movements and behaviors. This is equivalent to *I1:* copying the behavioral habits and movements from a known interaction or relationship (e.g., human-to-animal relationship) to a new human-to-system relationship. Designers transfer known relationship patterns to artificial (unknown) subjects [7]. It resembles making decisions for a system design, in which a *C1:* conventional approach [31, 37] or tool [60, 72] is transferred and reused for another system to *C2:* comply with users' expected system behaviors. This also suggests to *C3:* look at

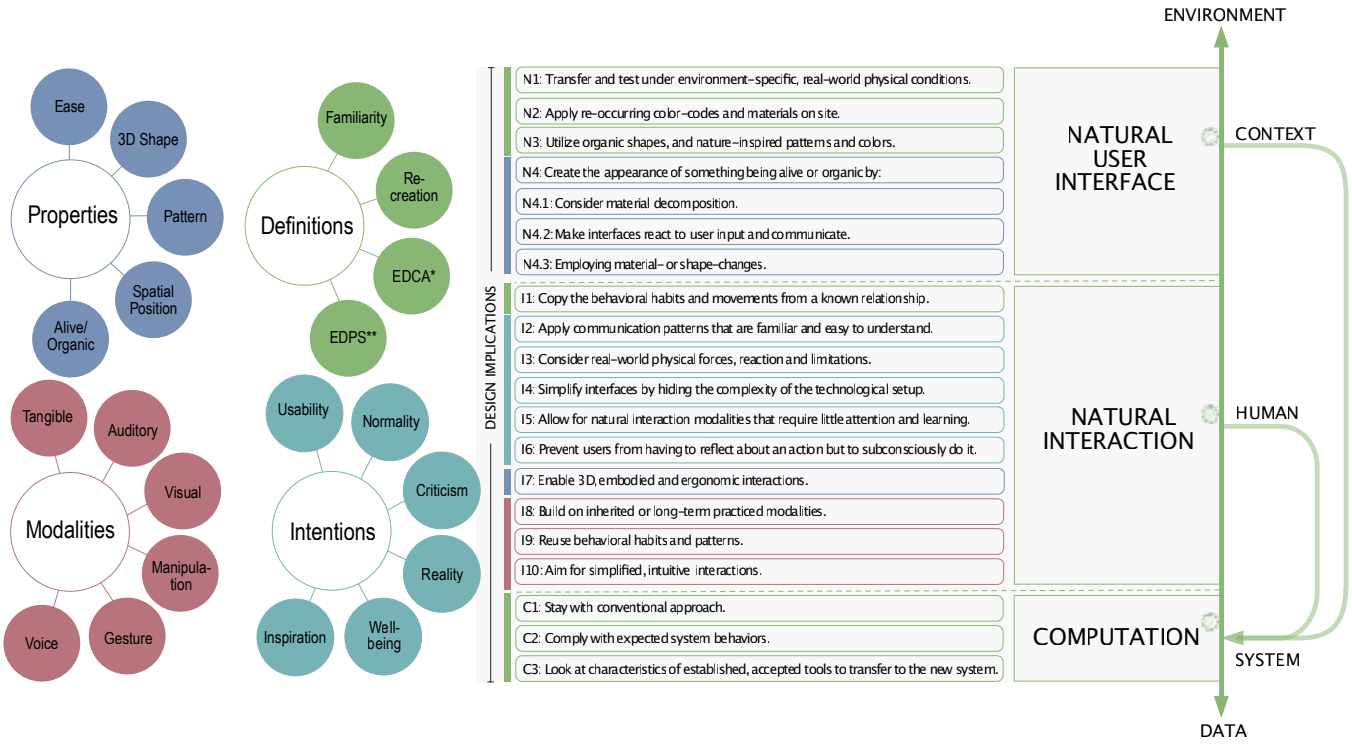

Figure 5: Natural Design for Interaction: The model consolidates our design implications based on our findings. We mapped them to either natural interaction, NUI, or computation and linked the design subjects, context, human, or system to it. *EDCA: Expected Design Choice or Alternative. **EDPS: Expected Design Principle or Strategy.

characteristics of established, accepted tools to transfer to the new system.

5.2.2 Intention Implications. The intention cluster reports on the design goals of applying Natural Design. It shows three main trends: a) applying Natural Design to facilitate a direct user interaction or b) indirectly influencing a user's mindset or behavior, or c) critically reflecting on its limitation deriving from copying realistic conditions and thus, also its limitations and restrictions. To facilitate interaction, our results suggest to *I2:* apply communication patterns that are familiar and easy to understand, such as visual or auditory icons [1, 40, 48] and *I3:* consider real-world physical forces, reaction and limitations, such as gravity and spatial restrictions [73, 88, 96]. Additionally, interaction tasks should be *I4:* simplified, hiding the complexity of the technological setup, and *I5:* allow for natural interaction modalities that require little attention and learning, such as gesture, voice, or touch [38, 44, 61]. The indirect influence aimed to either calm users or to change their behavior subconsciously. Design implications include the application of *N3:* organic shapes and nature-inspired patterns and colors, such as flowers and green leaves [41, 65, 75]. There is clear domination on visual designs strategies. In contrast, when aiming to nudge behavior changes, changes are implemented into the environment that *I6:* prevent users from having to reflect about an action but to do it subconsciously [93]. Thus, in such contexts, Natural Design aims at subconscious, automatized, simplified triggers. However, the natural interactions techniques were also criticized for, partly, poorer performance or preventing to make use of a technology's full advantage [2, 10].

5.2.3 Properties Implications. Summarizing the properties, Natural Design increases fidelity and intuitiveness by applying familiar, recognizable shapes and *I7:* enabling 3D, embodied, and ergonomic interactions [44, 73, 88, 93]. The 3D shapes and the spatial positioning are realized by, e.g., occlusion or shadowing in visualizations. Furthermore, a naturally designed interface can be indicated by *N4:* appearing "alive". *N4.3:* Material- or shape-changes can trigger the appearance of something being alive or organic, including growing interfaces, color changes, etc. [41]. Other changes, such as natural *N4.1:* material decomposition, can also be implied through a patina or used-look effect [40]. Additionally, to make an interface appear alive, the interface needs to be able to *N4.2: react to user input and communicate* [41].

5.2.4 Modalities Implications. 3D, physical interfaces enable tangible interaction, which is the main mentioned Natural Design modality [10, 40, 48, 78, 93]. Besides, researchers referred to gesture and voice input and output as embodied and familiar modalities and thus, Natural Design [44, 81, 93]. Accordingly, interactions modalities should be enabled that *I8:* build on inherited or long-term practiced modalities and which require little attention and learning. Natural Design interaction modalities are defined by how much they comply with the user's physiology and, in line with

the implications above, by movement and communication habits. Thus, *I9:* behavioral habits and patterns should be reused in the design. It includes the *I3:* consideration of surrounding conditions and interaction consequences (cf. [88]) and focuses on *I10:* simplified, intuitive interactions that require little learning effort.

6 DISCUSSION, LIMITATIONS, AND OUTLOOK

Our design implications responded to how Natural Design can be applied for interaction, considering different perspectives, system-, human-, and environment-centered, and application areas, computation, natural interaction, and NUIs. The variety of implications in-between these perspectives also shows that there is no one clear, unambiguous understanding but that the meaning of the term always depends on the context. Below, we discuss the benefits and limitations of Natural Design for interaction, including its potential to design different types of intuitive and embedded interfaces and how it relates to other approaches outside HCI.

6.1 The Meanings and Potential of Natural Design within HCI

Our results showed no shared, unique meaning of Natural Design within HCI. Instead, the most common understanding across application areas is that it is applied to create familiar and intuitive design subjects that require little cognitive workload (cf. [7, 40, 60]). Furthermore, it shows that Natural Design is mostly context-depending, including considering users' habits and behavior patterns.

Nonetheless, we also saw recent work increasingly applying Natural Design properties to improve the user experience and immerse the users more in their interaction, e.g., [6, 7, 29, 67]. This implies a need to share experiences among HCI researchers about how, when, and to what extent Natural Design can and should be applied. There is a common understanding of what defines a natural interaction [4, 13, 58, 92] or a natural user interface [17, 62, 76, 79], but little about a consolidated Natural Design approach on how to implement either. Here, we see the value of our model in Figure 5 and our cluster in Table 1 by providing the terminology, structure, and design implications for a common design basis. Thus, when talking about Natural Design, people can clarify their intentions using the term and the concept, which further has the potential to improve the communication and collaboration between researchers and designers across application areas [36].

We also see potential in encouraging Natural Design considering the current shift from human-computer interaction to human-environment interaction in HCI [80]. This shift requires integrating and embedding technology into the environment not to interrupt but still convey their interactivity. Thus, Natural Design can support bridging this gap by making use of, e.g., the nature-inspired design [10, 41, 65] in combination with fostering an intuitive, simplified interaction based on the users' behavior patterns and prior knowledge [7, 40, 61]. If compared to e.g., Wigdor and Wixon [94], it extends natural interaction and NUIs in the sense of supporting also beyond-the-human designs and for the design for different types of environments. There are first attempts that explore Natural Design to embed interfaces into outdoor environments, which confirm our statement [39]. However, projects are still scarce at the current point and will need further validation.

6.2 Limitations of Natural Design within HCI

One of the main criticism against Natural Design stems from the complexity and potential inefficiency of transferring real-world conditions [27, 62]. However, the attempt of reusing familiar (human) features, behavior patterns, and looks aligns with our findings. For example, the uncanny valley phenomenon [59, 77] describes the negative emotional effect on humans if virtual characters appear almost realistic and human-like but still somewhat faulty [5, 67]. Researchers still struggle to transfer these insights to robots, causing negative user experiences in the interaction with robots [5, 67] by applying a too natural yet faulty user interface. Similarly, there are limitations regarding natural interactions. For example, Bowman et al. [10] discussed cycling activities in Wii sports games, in which users interact via hand-held controllers. To mimic the habitual movement pattern of riding a bicycle, users had to imitate the arm movement. However, mapping the activity to another body part turns the embodied movement into a recognizable yet unusual movement. In such cases, simple, artificial designs might be better than allocating habitual movement patterns to the novel system. Alternative design approaches might derive from, e.g., Reality-Based Design[42], in which designers ground their creations along real-world conditions but optimize where necessary. It also reveals the need for evaluation tools to test whether an interface is naturally designed in the interaction, its appearance, and its contextual embeddedness.

6.3 Study Limitations

We weighed the survey's comprehensiveness against a transparent, systematic methodology and clarity and decided to favor the latter. Accordingly, our work focuses on a single keyword search in the ACM DL, the most relevant source for interaction papers, instead of including related design approaches and concepts within and outside HCI. While this limits the scope of our literature review, the results already included a very diverse understanding and usage of the term. Thus, we chose to follow the same approach as prior research [83] and focused on researching Natural Design for Interaction within the HCI community.

6.4 Looking Beyond the HCI Community

The diverse meanings of Natural Design and its intention to apply it align with the different approaches presented at the beginning of the paper. This part compares commonalities and differences between the Natural Design approaches. Thus, we discuss potential synergies and antagonisms.

Beginning with *philosophical behaviorism*, the field's definition relates to our derived understanding that Natural Design includes the reuse of behavioral patterns and habits (see Figure 5; implication I1, I2) and should allow for embodied interaction [85]. However, Natural Design in this field also limits its scope by making biological abilities a foundation of Natural Design. It antagonizes the Natural Design of systems or any artificially-created object, vastly reducing its applicability for the HCI community. Thus, while philosophical behaviorism seems to align with our understanding of Natural Design on a human level, there seems a somewhat divergent use and understanding of it otherwise. In contrast, *sustainable design* makes use of biomaterials and nature-inspired mechanisms (biomimicry

and biophilic desig [8]n) that may be a valuable extension to our current design implications, particularly for material designers. Biophilic design can further extend our current work by providing a deeper understanding of the psychological impact of the environment on its users and vice versa [12, 70] when designing Natural Design contexts.

Overall, the Natural Design from sustainable design provides a holistic perspective on naturally designing for different ecological and cultural contexts by combining approaches, methods, and tools from other research fields. We see great potential for future work on the intersection of sustainable Natural Design and Natural Design for interaction expertise within the HCI community considering the design of seamlessly embedded interfaces and calm environments.

7 CONCLUSION

We identified Natural Design as a valuable, context-depended design approach to create easy-to-use, intuitive, and embodied interactions and interfaces. In total, we derived 20 design implications for the application context of NUIs, natural interaction, and computation. Altogether, our work provides a structured overview of the different Natural Design meanings enabling cross-field collaborations within and outside HCI. Our systematic literature review showed that the most supported clusters within HCI used the term Natural Design as *Inherent or Acquired Familiarity* with the goal to *Design for Usability* by utilizing *Easiness* and *Tangible Interaction*. Furthermore, Natural Design connects nature-related and -inspired features to behavioral patterns and learned abilities, making it a potential design approach to seamlessly embed interfaces into environments that stay recognizable to the user. Considering the current shift toward human-environment interaction in HCI, Natural Design might, thus, be a supportive approach to tackle this challenge. However, we also identified real-world, natural characteristics that may limit the user experience or be too complex to be transferred onto a design. Thus, designers need to carefully consider the purpose and context to apply Natural Design and test their designs under the natural conditions of the target environment before deployment.

ACKNOWLEDGMENTS

We want to thank Changku Ou – the digital data visualization king – for his help to set up our web tool.

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