Morphino: A Nature-Inspired Tool for the Design of Shape-Changing Interfaces

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ABSTRACT
The HCI community has a strong and growing interest in shape-changing interfaces (SCIs) that can offer dynamic affordance. In this context, there is an increasing need for HCI researchers and designers to form close relationships with disciplines such as robotics and material science in order to be able to truly harness the state-of-the-art in morphing technologies. To help these synergies arise, we present *Morphino*: a card-based toolkit to inspire shape-changing interface designs. Our cards bring together a collection of morphing mechanisms already established in the multidisciplinary literature and illustrate them through familiar examples from nature. We begin by detailing the design of the cards, based on a review of shape-change in nature; then, report on a series of design sessions conducted to demonstrate their usefulness in generating new ideas and in helping end-users gain a better understanding of the possibilities for shape-changing materials.

Author Keywords
Shape-changing interfaces; bioinspiration; nature; toolkit

CCS Concepts
•**Human-centered computing** → *User interface toolkits; Activity centered design;*

INTRODUCTION
In recent years, many human-computer interaction (HCI) researchers have explored and revealed the numerous advantages of shape-changing interfaces (SCIs); that is, interfaces that are not limited to rigid and flat surfaces but can exhibit shape deformation and non-planar forms [2, 88, 97]. This interest in reconfigurable interactive devices for end-users has led to the emergence of new interaction paradigms where users can mold their devices or instruct them to reconfigure their form to better suit a task. Designing the next generation of SCIs requires designers to discover new insights into morphing technologies, and to harvest interdisciplinary skills from other research fields, such as material science, robotics and physics.

Figure 1. *Morphino* card deck.

The need for better synergies between scientific fields has already been highlighted by several HCI researchers [2, 87]. In an early attempt to address this challenge, Qamar *et al.* [87] reviewed morphing technologies in material science and discussed how these could be harnessed by HCI practitioners in developing SCIs. The authors identified the need for a set of tools to facilitate the adoption of these mechanisms, and created an online database, *MorphUI* [75], to enable outputs across different fields to be more readily accessed.

Here, we take a step further by incorporating Qamar *et al.*'s shape-changing mechanisms into the development of a nature-inspired tangible design toolkit—*Morphino*—for researchers in SCIs to use, whether this be students learning about interaction design, or for more advanced researchers to readily access forms of bioinspired shape-change for new research directions or to solve present research problems. *Morphino* consists of a set of cards with examples of shape-change in nature, and each card is linked to one (or more) morphing mechanisms found in the *MorphUI* database. *Morphino* aims to: (1) provide HCI researchers with a new source of inspiration for designing SCIs using examples from nature; and, (2) improve synergies between fields by linking these examples to an existing database containing methods for transferring their designs into real-life prototypes.

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We design our toolkit based on morphing in nature, since nature has inspired the development of physical and computational models, engineering systems and technological designs in many fields; for example, the streamlined shape of the Shinkansen bullet train in Japan was inspired by the bill of the kingfisher to improve aerodynamic efficiency [55]; hook-and-loop fasteners (Velcro) were designed after burrs of the burdock plant for adhesion [116]; WhalePower wind turbine blades were modelled after the flippers of humpback whales to reduce noise, increase stability and capture more energy from the wind [126]. Most bioinspired activity, however, is directed towards the development of materials or structures, not towards creating new methods of interaction nor towards enhancing user experience with SCIs.

We begin by explaining the design of *Morphino* based on a review of morphing in nature. Following this, we conducted a study to understand how bioinspiration can affect the ideation of SCIs, and to establish whether the card deck could facilitate the implementation of these ideas.

RELATED WORK

We discuss the literature regarding bioinspiration in material science, robotics and HCI, and different types of design tools: SCIs, card-based, and bioinspired.

Bioinspiration in Material Science and Robotics

Scientists and engineers have often looked to nature for inspiration in designing strong, yet light structures that can change shape. Examples of bioinspiration in robotics can be found at varying length scales [62, 114], for example, in a robotic joint inspired by jumping spiders [104], in worms that can be driven through low-voltage current [92], in soft sheet actuators that generate waves for locomotion similar to gastropods [124] and in the implementation of rolling in robotics [8]. At a larger scale, Xie *et al.* [131] explored different octopus species for the design of soft actuators for gripping objects and Dementyev *et al.* [29] designed a skin-crawling robot for measuring a range of body parameters, inspired by an inchworm mechanism. In material science, there has been a growing interest towards 4D printing of shape-changing materials inspired by the anisotropic properties of plant structures [40, 81].

Robotic systems, in particular, are often developed with the intention of being placed far away from human activity, where resilience is a desirable property [72, 100]. There are a few examples of how biologically-inspired robots interact with users [1, 56, 105], however, while important factors in robotics include anthropomorphism, animacy, likeability, perceived intelligence and perceived safety of the robot [11], the significant factor within HCI systems is the user experience.

Bioinspiration in HCI

In [51], the authors highlight how nature is a key source of inspiration in the design of flexible and adaptable shapes for interactive displays to improve usability and affordance. We can find many examples in HCI, demonstrating the growing trend towards bioinspired design in this field. At a small scale: Kan *et al.* [58] explored colour, odour and shape-changing materials through organic molecules that react to *pH* change. Yao *et al.* [132] explored how living *Bacillus subtilis* natto cells could be used to create humidity sensitive nanoactuators for SCIs. Wang *et al.* [122] investigated the use of microbial cells to create films that can reversibly change shape and biofluorescence for wearable technologies.

At a larger scale: Cheng *et al.* [21] presented *Mood Fern*: an artificial plant with leaves that respond to touch, similar to the sensitive *Mimosa* [125]. The leaves are actuated using shape memory alloys. Golhke *et al.* [42] developed and evaluated bioinspired SCIs made from soft or malleable materials with fluidic actuation. Wang *et al.* [123] exploited the hygroscopic properties of protein, cellulose and starch to create shape-changing food. A similar principle has also been applied to create self-folding 3D printed objects actuated by heat [6].

Design tools for SCIs

There has been a growing drive in the HCI community to develop interfaces that can change their shape as a new method for interaction with computers [2]. Several review papers have been published in HCI that define different types of shape-change and their applications within interactive systems:

- Rasmussen *et al.* [88] presented a review of existing work on SCIs and identified eight different types of deformation: *Orientation*, *Form*, *Volume*, *Texture*, *Viscosity*, *Spatiality*, *Adding/Subtracting* and *Permability*.
- Roudaut *et al.* [97] proposed the term *shape resolution* that extends the definition of display resolution to SCIs. It is based on the model of Non-Uniform Rational B-splines (NURBS) and has ten features to characterise shape-change mathematically. Kim *et al.* [61] refined this taxonomy to include two new features: *Size* that incorporates *Length*, *Area* and *Volume*, and *Modularity*.
- Sturdee *et al.* [108] contributed a meta-analysis of shape-changing design theory, along with a database of shape-changing prototypes and a categorisation of types of SCIs including *Enhanced 2D*, *Bendable*, *Paper and Cloth*, *Elastic and Inflatable*, *Actuated*, *Liquid*, *Malleable*, and *Hybrid*.
- Coelho *et al.* [26] adopted a technology-driven approach with a taxonomy describing the technological properties of shape-changing devices, including: *power requirements*, the *ability to memorise new shapes*, and *input stimulus*, such as voltage potential, or the *ability to sense deformations*.
- Qamar *et al.* [87] proposed a series of categories that focus on the mechanisms behind shape-change and created a database—*MorphUI* [75]—to enable researchers in HCI to access outputs from material science (see Figure 2).

Through a series of sketching workshops, Rasmussen *et al.* [89] demonstrated that there are some instances in which shape-change defined by shape vocabulary may be insufficient due to the complexity of the transformation. The authors highlighted that the existing vocabulary needs to be further developed or to be accompanied by (i) *the dynamic physical properties of its changes in shape*, (ii) *what the new shape entails for the user*, and (iii) *how the actual interaction with the interface occurs*. Sturdee *et al.* [109] also proposed *design fiction* on the subject of SCIs as an approach that could add value to application and further prototype development.

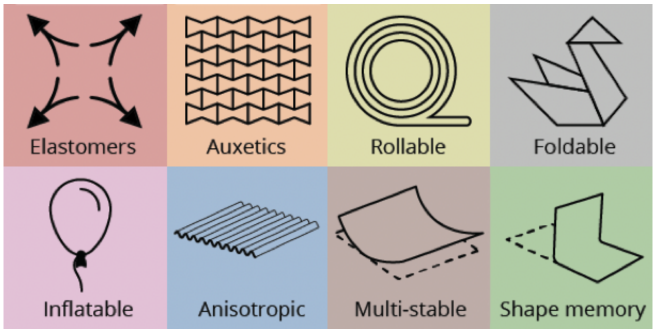

Figure 2. Mechanisms of shape-change from the *MorphUI* database [87]

Summary: We can draw two conclusions: First, Qamar *et al.*'s review [87] is the only attempt thus far to create a bridge with other disciplines of science for designing SCIs; Second, current tools exist primarily for the early stages of idea generation and transfer tools that enables these ideas and solutions to be turned into real-life prototypes are still lacking. *Morphino* is the first step towards this goal by linking the mechanisms of shape-change in nature to an existing database of material science and HCI research.

Card-based design tools

Card-based tools have already proven to be versatile and efficient for problem-solving: they are tangible idea containers that help support divergent thinking and the exploration of design spaces, they enable collaboration, and they trigger combinatorial creativity [14, 65, 71]. Cards typically contain text, symbols and pictures, and are often colour-coded to form categories, which, combined with a set of rules, help to inspire and guide the co-design process [12].

Wölfel *et al.* [130] offer a comprehensive review of eighteen card-based design tools and define them in terms of five design dimensions including: the *intended purpose and scope of use*, *duration of use*, *methodology*, *customisation*, and *formal/material qualities*. The authors identified three patterns and suggested that designers should consider one of the three main archetypes in the creation of new card sets:

- *General purpose/repository cards* that can be used anytime during the design process and have basic or no instruction for use. The cards are often sorted into different categories without the option for customisation.
- *Customisable cards* that typically offer some degree of customisation; for example, giving the designer an option to add notes to the cards, or to add additional cards to the card deck. These cards tend to belong to the participatory design group, with specific instructions for use and are mainly used at a specific point in the design process.
- *Context specific cards* that are developed with a specific design agenda or context in mind, and are therefore designed to be used primarily at a specific point during the process with specific instructions.

Within HCI, card-based kits have been developed across several themes; for example, in the Internet of Things design space, *Know-Cards* [10] contains 162 cards across four categories (*input*, *output*, *power*, *connection*), that represent the technical building blocks of smart objects. Card-based design tools such as PLEX [70] and Positive Emotion Granularity Cards [133] consider the emotional qualities of interaction, whereas *IDEO* [53] contains *Learn*, *Look*, *Ask* and *Try* cards to help designers plan projects and to suggest ways to approach human-centred methods throughout the process.

Summary: While card-based design kits already exist within HCI, there are a lack of tools specifically for designing SCIs. By creating a set of cards that offer open-ended inspiration for shape-change and linking them to existing literature on morphing materials, we aim to inspire researchers early during the brainstorming process while also offering a method repository to help provide solutions to problems that may occur at any stage during prototype development.

Bioinspired design tools

Several design frameworks enable researchers to draw inspiration from nature in a systematic way. Fu *et al.* [36] proposed an overview of bioinspired design tools that target the design process. The *Biomimicry 3.8 + Packaging Innovation Toolkit* [13] is a design method with a taxonomy to help users develop sustainable solutions by looking to forms, processes and ecosystems in nature. It includes *Nature's Technology Summaries* cards that describe biological strategies with a high relevance for packaging products, and *Riffler* cards aimed at enticing a larger exploration of the design space beyond "obvious" ideas. *AskNature* [9] is a web repository of approximately 1,700 biological strategies (classified around *Biomimicry 3.8*) and 200 design ideas inspired by nature, directed at answering innovative design challenges. *Design by Analogy to Nature Engine (DANE 2.0)* [24] is an interactive tool to support biologically inspired design and is based directly on a Structure-Behaviour-Function (SBF) ontology [41]. The tool contains a collection of biological models for inspiration that are ordered and indexed by function and link to behavioural causal explanations, along with structure box diagrams.

Fayemi *et al.* [34] reviewed existing processes, tools and practices for applying principles and strategies from biological systems to engineering and technological designs. They presented a model of a problem-driven process and conducted a series of workshops to assess the existing tools and methods, such as *AskNature*, in order to develop a utility tree which will help users select the most appropriate tools for implementing bioinspired and biomimetic design in their own context. They highlighted that developing transfer tools (i.e. taxonomies) in combination with application tools (i.e. databases) is key to the development of bioinspired technologies.

Summary: While these studies begin to show how nature can inspire new interfaces between users and computers, no systematic tool has yet been proposed to facilitate bringing bioinspiration into the design process of SCIs or to help users transfer their ideas into tangible prototypes. *DANE 2.0* [24] describes the major challenges of bioinspired design as (1) finding biological systems that are relevant in a design context, and (2) understanding those systems so one can extract and transfer the appropriate working principles. We develop *Morphino* with the aim to address these challenges.

MORPHINO OVERVIEW

Morphino is a nature-inspired, card-based toolkit for the design of SCIs. It includes a card deck, concept boards and is linked to an existing database of shape-change research. Although we propose a procedure in our design sessions, the cards may be used freely, both during the early stages of design or when looking for alternative solutions to solve a design problem.

For the design of our cards we took inspiration from existing card-based kits such as [44] and [53], however, these focus on different design contexts. We also tried to extend the *Biomimicry 3.8* deck, yet this was unsuccessful as these cards focus on creating new structures and materials rather than designing for interaction. To place *Morphino* within existing card-based kits we used the review by Wölfel *et al.* [130] and found that our approach lies within the *general purpose/repository* cards that offer either a method repository or aim to stimulate inspiration and lateral thinking.

Each card has two faces: a title and image on one side and an explanatory text on the back (Figure 3). A rotoscope on the front helps users quickly understand how that organism changes shape. A series of symbols on the reverse, referencing the *MorphUI* [75] shape-changing mechanisms, provide ideas of how designs could be implemented by linking to an online database of existing research. The categories in this database include: *Elastomers*, *Auxetics*, *Rollable*, *Foldable*, *Inflatable*, *Anisotropic*, *Multi-stable* and *Shape memory* (see [87]). Below, we provide the review on which the cards are based, and the full deck can be found in the *Supplementary Materials*.

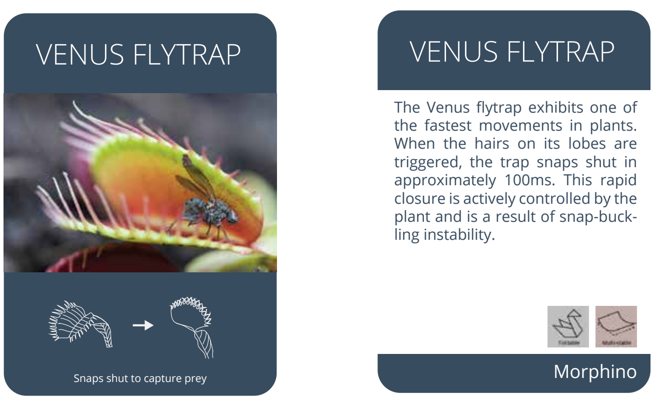

Figure 3. An example *Morphino* card: Venus flytrap.

MORPHINO CARDS

Morphing in nature has caught the interest of researchers across many fields – from material science to robotics, to medicine – due to the relatively large structural changes that can be achieved with mild, ambient conditions and limited chemical diversity [81]. While some of these mechanisms have already been reviewed [81], here, we place an emphasis on linking nature examples to existing literature.

In creating the cards, we selected 2-3 distinct examples from each section below. Each example was linked to one or more categories from the *MorphUI* database [75], depending on the mechanism behind the shape-change, to provide methods for implementation. These are summarised in Table 1.

Stretching in nature

Stretching in plants and animals is largely due to elastomeric proteins (elastomers). Elastin, for example, is found in elastic tissues in the human body, including those of arteries, skin, lung and in cartilage. It gives the tissue a rubber-like property, enabling it to return to its original shape after being poked, pinched, stretched or contracted [99].

The jumping and flying mechanisms of insects, such as fleas, are enabled by resilin which is found in specialised cuticle regions located near the hind leg [7, 32]. This elastomer acts like a spring and enables a flea to be catapulted into the air in less than 1 ms, once all the stored energy in the 'spring' is released [19, 96]. Abductin also enables a spring-like hinge mechanism in molluscs. The adductor muscle, which keeps the shell closed, is opposed by an inner hinge ligament made from abductin that causes the shell to spring open [57]. Repeated opening and closing of the valves enables the swimming movement of many bivalve molluscs such as scallops, which can open and close their shells about four times per second to swim the distance of a few meters and escape slow-moving predators [59, 120].

Spider silk behaves like rubber, yet it is one of the lightest, strongest materials known to man. Spiders use their silk for creating webs, wrapping prey, protecting offspring and as a roping line to quickly evade predators. Arachnids produce many types of silk; "Dragline" (or MA) silk is the toughest silk produced by spiders and is used for abseiling or for framing webs. It is very stiff, yet when immersed in water it undergoes super-contraction by up to 55%, increasing its extensibility [43]. Flag silk makes up the capture spiral of an orb web and is highly elastic, enabling it to dissipate impact energy of prey through stretching of the spiral threads [95, 121].

Unlike elastomers, auxetic materials get fatter when they are stretched as opposed to thinner. Their internal geometry is usually engineered to enable this shape-change, however, a few examples exist in nature, including nacre (mother-of-pearl) [103], cancellous bone [128] and cat skin [117]. Cow teat tissue also displays auxetic properties and behaves like a knitted fabric. This allows for a change in internal volume when the teat is full of milk and is being suckled or milked [68].

Inflation in animals

Animals increase their size to communicate; for example, to display deimatic behaviour or to signify and attract. Some animals inflate for more functional means, such as to prevent grasping by predators or to act as a deployable flotation device.

Deimatic behaviour:

Pufferfish, hooded seals and cobra snakes are a few examples of animals that inflate their bodies or parts of their bodies to find mates or to defend against predators. The long-spined porcupinefish can inflate itself by pumping water into its stomach, increasing the volume of its body by up to three times its original size. As the fish swallows water, the pleats of its stomach unfold into an existing peritoneal space. The collagen fibres in the skin become stretched and the skin suddenly becomes stiff, providing a rigid structure to support the spines, which results in a highly effective mechanical defence system [17].

Organism	Categories	Organism	Categories	Organism	Categories
Human skin	Elastomers, Auxetics, Shape memory	Bat wings	Foldable, Anisotropic	Sea cucumber	Elastomers, Inflatable, Shape memory
Flea legs	Elastomers, Multi-stable	Peacock train	Foldable	Starfish	Elastomers, Inflatable, Shape memory
Mollusc hinge	Elastomers, Foldable, Multi-stable	Hornbeam leaf	Auxetics, Foldable	Octopus arms	Elastomers, Rollable, Inflatable, Shape memory
Spider silk	Elastomers, Auxetics	Ice plant	Foldable, Anisotropic, Shape memory	Cuttlefish skin	Inflatable, Foldable
Cow udder	Auxetics	Pine cone	Foldable, Anisotropic, Shape memory	Venus flytrap	Foldable, Multi-stable
Porcupinefish	Elastomers, Inflatable	Tree branches	Anisotropic	Bladderwort	Multi-stable
Female cane toad	Inflatable	Three-banded armadillo	Rollable	Bittercress siliques	Rollable, Multi-stable
Frigatebird	Inflatable	Golden wheel spider	Rollable	Wheat awns	Anisotropic, Shape memory
Walrus	Inflatable	Mother-of-pearl moth caterpillar	Rollable	Sensitive plant	Foldable, Anisotropic, Shape memory
Ladybird wings	Foldable	Butterfly proboscis	Rollable, Multi-stable	Cucumber tendril	Rollable, Shape memory

Table 1. Morphino cards generated, linked to the respective categories from the *MorphUI* database [87]

When threatened, snakes commonly inflate their bodies to appear larger than they are; for example, puff adders inflate their entire bodies vertically and produce loud hisses as a warning to other predators, compensating for their relatively slow movement capability [134]. The female cane toad inflates itself as a defensive mechanism to thwart successful takeovers from rival males by preventing the males from grasping [18].

Courtship display:
Several species of birds inflate brightly coloured parts of their bodies to attract mates. Usually this is combined with a series of vocal calls. The frigatebird inflates a bright red gular pouch as a display of courtship, enabling the male bird to give a variety of calls such as drumming, reeling and purring [30]. The sage grouse exhibits a strut display comprising of the inflation of the male's esophageal sac, which is flaunted and simultaneously used to produce a sound [127]. Bustards also inflate their gular pouch in a courtship display [28].

Inflating for flotation:
When a walrus is ready to sleep, it directs air into chambers in its throat called pharyngeal pouches to create a natural pillow and flotation device, keeping its head above water. The sacs are also used to make sounds during the mating season [73].

Origami-like folding in wings and plants

Some of the most intricate folding patterns that exist can be found in the wings of animals, such as ladybirds, and in the leaves of plants, such as the Miura folds in the hornbeam leaf.

Folding of wings and feathers:
Ladybirds and other beetles can fold and unfold their wings in a fraction of a second, transforming from a walking insect to a flying one. Their hind wings are hidden underneath the hardened forewings (elytra) whilst the insects are on the ground and unfold just before flight [80]. Saito *et al.* [98] showed that the wing veins have a curved shape (like the carpenters tape) that plays a crucial role in enabling the wing to be rigid when extended but stable when bent and folded for storage. The ladybird first closes its elytra and then uses its shell to press down on the hind wings, triggering them to fold based on an intricate origami-style crease pattern (Figure 4(A)).

Bat wings consist of a highly anisotropic membrane containing tiny muscles that control the membrane tension [111]. The wings are manoeuvred skeletally through a series of flexible bones with independently controllable joints, providing greater than 20 degrees of kinematic freedom per wing. This enables a high degree of control over folding and extension of the wing [23, 94]; however, they are unable to initiate the same degree of control in their wing area due to slacking in the wing membrane [85]. Birds can change their wing shape and maintain aerodynamic efficiency until the wings are tucked up against the body, due to overlapping feathers that are controlled by musculoskeletal mechanisms [86]. They have an anatomy similar to human arms with an upper arm, lower arm and hand connected to the body through the shoulder joint. This enables birds to soar and glide in the air and adjust wing sweep mid flight, but also independently fold each wing so they can fly through small gaps not much larger than their body [107]. Peacocks unfold the long upper-tail feathers of their train and raise them into a fan in a visual display of courtship [69].

Folding in plants (corrugation):
Wave-type, origami-like folding is also common in plants. Some leaves, such as those from the common beech and hornbeam, have a corrugated 'Miura-ori' pattern, enabling them to unfold as they emerge from the bud (Figure 4(B)) [118]. This pattern allows simultaneous extension in two perpendicular directions [27] and the greater the angle of corrugation from the centre vein, the more compactly the leaf can be stored but the longer it takes to unfold. [64]. Maple leaves have a more complex, fan-type bellows pattern with seven elements of corrugation, each connected to its neighbour [63].

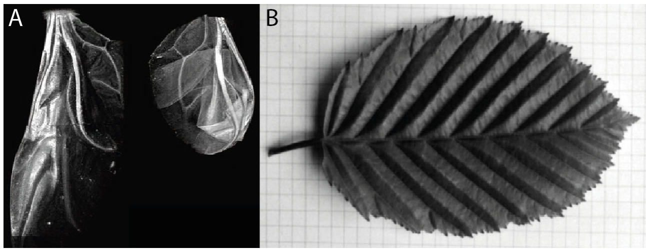

Figure 4. (A) Micro-CT scans of an unfolded (left) and folded (right) ladybird wing [98]; (B) A typical hornbeam leaf with corrugation [64] ©1997 image reproduced with permission from the Royal Society.

Folding in plants (hygromorphic actuation):
A hygromorphic material is one that changes its geometry in response to environmental humidity; its cellular structure swells when the humidity increases and shrinks during drying. The seed capsules of the ice plant exhibit hydro-actuated origami-like unfolding. When dry, five protective valves cover the seed compartments, preventing premature dispersion of seeds. When hydrated, each valve unfolds outwards and backwards over an angle of 150° within minutes. This is a reversible movement due to anisotropic swelling of cellulose within the plant cells [46]. Like the ice plant, pine cones are also hygromorphs, i.e. they respond to a change in relative humidity by opening their scales when it is dry and closing when it is damp, keeping the seeds contained [26]. As the cells of fallen pine cones are dead, the mechanism of opening and closing is passive and relies on the structure of the scales; the outer layer of tissue expands when humid and shrinks when dried, while the inner passive layer does not respond as strongly [91].

Anisotropy is an inherent characteristic of wood, which has different properties in three perpendicular directions; axial, radial, and circumferential, depending on the orientation of the grain. This enables a tree to have a structure stiff enough to support its weight, yet be flexible enough to bend in the wind or to achieve better leaf display or height growth [129].

Rolling for protection and locomotion:
Many animals roll to protect their body from predators or to alter their shape to move passively (under the influence of gravity or wind) or actively by generating a propulsive force.

Rolling for protection:
Pangolins and three-banded armadillos have armoured shells made up of scales for protection. When threatened, these animals curl into a ball and tuck in their tail to protect themselves from predators [47, 90]. Similarly, the armadillo girdled lizard has a thick armour on its body and sharp spines on its tail and limbs. When threatened, this lizard takes its tail in its mouth and rolls into a donut-shaped ball, using its armour and spines as a shield [79]. Hedgehogs roll into a ball and use their spines in a similar defence mechanism [48], however, it has been suggested that the primary function of the spines is as a shock absorber when a hedgehog falls from a height [119]. Several insects also roll for protection, including isopods, such as woodlice [25], myriapods, such as centipedes and millipedes [22], and caterpillars, which cannot move quickly due to their long body and movement mechanism: the travelling hump.

Rolling for locomotion:
Animals that use passive rolling to escape predators include the web-toed salamander, the golden wheel spider and some types of woodlice – it enables them to achieve much higher speeds than they would otherwise. The golden wheel spider, for example, begins running, then flips its body sideways, curls its legs into semicircles, and rotates down smooth sand dunes, escaping predatory wasps by blurring its outline [49]. When disturbed, the salamander can also assume a coiled position and roll down the volcanic slopes in which it lives [38].

Some animals use active rolling to escape: the larvae of the mother-of-pearl moth caterpillar lacks some of the protective mechanisms of normal caterpillars, such as irritant hairs on its body; however, within 60ms it can coil itself into a ball and freewheel backwards away from danger [16]. It's movement is driven by a series of impulses; a characteristic also displayed by the stomatopod shrimp which does backward somersaults when washed up on a beach [20, 37].

Rolling for storage:
Butterflies and moths have a proboscis that is normally stored as a spirally coiled structure beneath the head of the insect. For feeding, the tube is unrolled in a similar manner to a measuring tape (with a stiffer "trough" section to keep it extended) and nectar is forcibly drawn through the tube [50, 66].

Stiffness- and texture-change in marine animals
Due to their tissue structure, some marine animals have the unique capability to change their stiffness (e.g. sea cucumbers, starfish) or skin texture (e.g. octopus, cuttlefish).

Hydrostatic skeletons:
Echinoderms, such as starfish, sea urchins and sea cucumbers, can rapidly and reversibly change the stiffness of their connective tissues for locomotion and protection. Under control of the nervous system, the mutable collagenous tissue can alter from soft to hard within seconds due to changes in the stiffness of a protein-rich interfibrillar matrix that bonds with the collagen fibrils [74]. This enables the sea cucumber, for example, to be flexible enough to move and squeeze through narrow cracks inside rocks for protection, and then become stiff enough to withstand large forces from surge currents, to bury themselves into the seabed, or when they are bitten and pulled by predators [76, 113]. A change in stiffness of the body of a starfish enables it to flex its arms for movement, yet become stiff enough to prize open a clam for feeding [77, 78].

Muscular hydrostats:
Octopus are able to exhibit many forms of shape-change. Their arms have the unique ability to stretch by up to almost twice their length, in addition to shortening, bending or twisting at any location. They have almost an unlimited number of degrees of freedom [67] due to their incompressible muscle tissue, the volume of which remains constant as it stretches and contracts, hence the term 'muscular hydrostat'. There is no skeletal structure; it is the muscle tissue that enables the arm to change its shape yet also generate a force [60].

Cuttlefish and octopus are able to change their surface texture for camouflage and signalling purposes [3]. A series of skin folds (papillae) enable the surface of these cephalopods to change from smooth to spikey in a matter of seconds, as a response to visual cues (Figure 5) [45]. This allows the animal to adapt to its surroundings and disguise its true outline [4]. The change in shape of the papillae is said to rely on a muscular hydrostat mechanism, where the support of the papillae is provided by muscle fibres rather than a skeletal structure, and the shape and degree of its expression can be controlled [5].

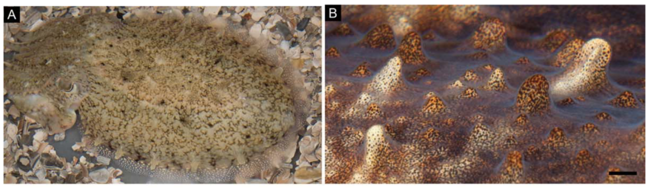

Figure 5. Left: Cuttlefish with many small dorsal papillae extended on the mantle, head and arms. Right: Close-up of small dorsal papillae [4] ©2013 image reproduced with permission from John Wiley & Sons.

Rapid movement in plants

Many plants exhibit rapid movement, be that for defence (e.g. sensitive *Mimosa*), for capturing food (e.g. Venus fly trap, bladderwort) or for pollen and seed dispersal (e.g. wheat awns, bittercress siliques) [101]. The Venus flytrap displays one of the fastest movements in plants: when the small hairs on the plant lobes are triggered, the lobes snap shut in about 100ms. This rapid closure is controlled actively by the plant as a result of snap-buckling instability [35]. The rootless, free-floating bladderwort is an underwater carnivorous plant. The stems below the surface have a series of long, hollow bladders attached, each with a trapdoor at one end. The pumping out of water causes a low internal pressure within the closed bladder, thereby creating an elastic instability in the bladder walls [102]. When the hairs protruding from the trap door are triggered, the trapdoor flexes inward and a pressure differential causes a sudden influx of water and the trapdoor shuts. The bladder then slowly resets to its initial state [93, 112].

The explosive dispersal of seeds is displayed by the sandbox tree [110], in fungus spores [82], in bittercress siliques [115] and in the filaree [33, 106]. As the bittercress plant dries, stresses develop in layers of the valve and a rapid loss of adhesion causes the valve to coil and the seeds to be flung away from the plant [115]. In addition to explosive (primary) dispersal, some plants, such as the filaree and wild wheat, also exhibit hygroscopic (secondary) dispersal [84, 106]. The dispersal unit of wild wheat has two pronounced awns. During the day when it is dry, the two awns bend outwards, whilst during the night when it is damp, they bend towards each other; the resulting drill-like movement pushes the seed into the ground, helping to increase its chance of survival [31].

Some leaves fold as a defensive mechanism; for example, in response to touch. Within 4-5 seconds of stimulation, the pulvini (organs containing motor tissue) execute curvature and the sensitive *Mimosa* quickly folds its leaflets and pinnae, drooping downward at the petiole attachment. The leaves also droop at night or when exposed to rain or excessive heat, preventing excessive loss of nutrients, and as protection from herbivorous insects or desiccation [83, 125].

A few plants, such as cucumbers [39], sweet peas [54] and grape vines [15], have coiling tendrils that they use to anchor themselves securely to trees and trellises and hoist up towards sunlight. During climbing, the cucumber tendril elongates its straight stem until it reaches something it can latch onto. It then forms a left-handed helix at one end and a right-handed helix at the other; the point at which the two helices meet is known as a “perversion” (Figure 6). This coiling shortens the stem and hoists the plant up towards the attachment point [39].

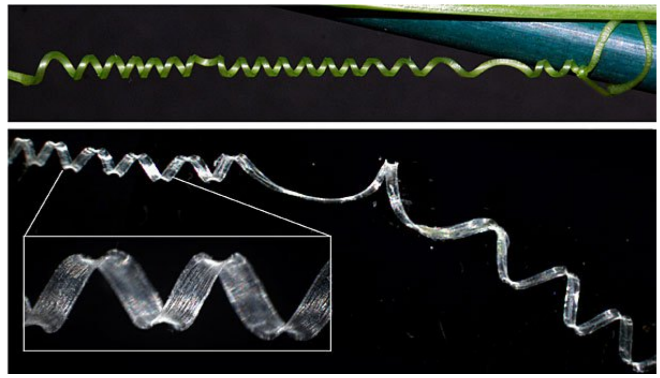

Figure 6. Helical morphology of a coiled cucumber tendril [39] ©2012 image reproduced with permission from AAAS.

DESIGN SESSIONS

We organised two sets of workshops across two institutions to determine how *Morphino* affects the ideation of SCIs and whether it guided users to learn about new morphing technologies from the material literature.

Participants

We conducted two workshops in country A and two in country B. In total, 17 participants aged 22-43 years old attended the workshops; 10 PhD students, 4 researchers and 3 lecturers participated, with HCI backgrounds ranging from haptics, to health to hand gestures for interface design. A few participants had experience in SCIs (3) and the remainder were knowledgeable of GUI, TUI and SCI. The same participants attended both workshops at each site, except one person who only attended workshop A #1 and was replaced in A #2. We ran the workshops in two countries to have access to a larger pool of participants. Two authors facilitated the workshop, but did not interact with the participants during brainstorming.

We used the same scenarios across the sites. During the first round of workshops (A #1 and B #1) participants were asked to brainstorm ideas for a *shape-changing handheld device, that adapts to different tasks, for use on public transport*. During the second round of workshops (A #2 and B #2) held one week after the first, their goal was to design a *large shape-changing display that could be used to communicate information in a school/university setting*. At each location we ran one workshop with *Morphino* and one without (see Table 2) and ensured a different scenario was provided each week to minimise any influence of the first round of workshops on the second.

Procedure

Each workshop lasted 60 minutes. We describe our procedure in the format of a step-by-step guide for using the cards:

1. **Introduction (5 min.)**: An introduction to the session was given to the participants, along with an explanation of the problem they have been given to solve. During the sessions with the toolkit, the *Morphino* cards were also explained. The participants were split into groups of 4.
2. **Brainstorming sessions (20 min. per session)**: The participants were asked to sketch and describe their ideas, using one "concept board" per idea (see Figures 7(A) and 7(B)). During the workshop with *Morphino*, they were asked to mention which card(s) were used to inspire their design.
3. **Idea selection (5 min. per group)**: At the end of the sessions, participants were asked to pick their 3 best ideas.
4. **Presentation (5 min. per group)**: The participants presented their ideas to other groups. The facilitator collected all worksheets for later analysis of the generated ideas.
5. **Feedback (5 min. per group)**: We held a group discussion with participants to understand how they generated ideas and, where appropriate, how they used the toolkit, its strengths and weaknesses, as well as potential uses. During the second workshop, the discussion included comparisons between generating ideas with and without the cards.

Analysis

The feedback from the discussion was recorded, summarised, and analysed thematically to establish key patterns and themes. We also counted the number of ideas generated by each group and per *MorphUI* category to identify different types of shape-change used by participants and to determine whether *Morphino* had an impact on this. All ideas generated in the workshops are available in the *Supplementary Materials*.

Findings: Ideas and feedback

Number and examples of generated ideas

In total, participants generated 102 ideas and the total numbers were similar for each workshop/location, regardless of whether the kit was used (see Table 2).

Workshop	Materials	Total no. of ideas
A #1	Morphino kit	29
B #1	No materials	23
A #2	No materials	28
B #2	Morphino kit	22

Table 2. Total number of ideas generated in each workshop.

Ideas generated by the kit included novel ideas, such as an inflatable conversation-starter to be used on a train, and a knowledge tree where the branches show the concepts that students have to learn and are stiff if mastered and soft if not; as well as less unusual ideas, such as a foldable drinks tray for tea and coffee on a train (Figure 7(A)).

Ideas generated without the kit included a table which changes its height to encourage movement, a phone that can be stretched from normal to widescreen mode for watching videos, and an interactive folding map with origami fold out landmarks (Figure 7(B)). In general, these ideas tended to conform to more 'traditional' shape-changing concepts.

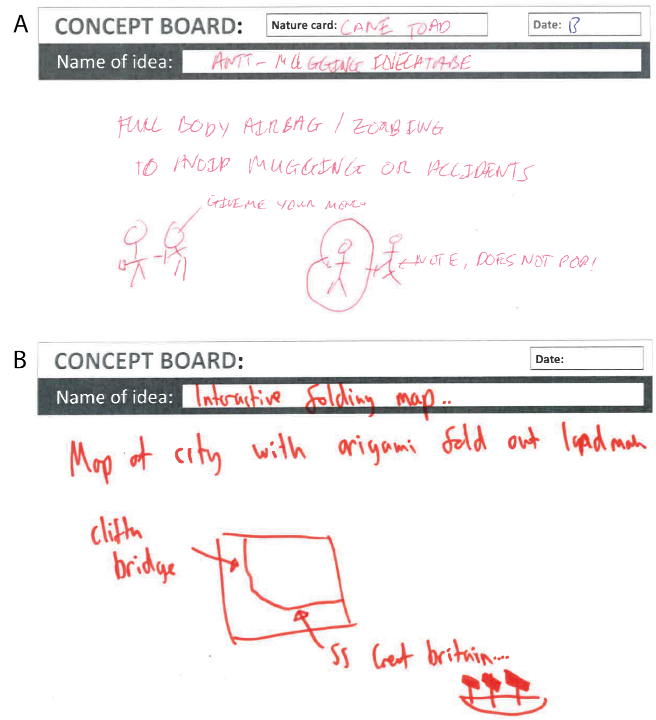

Figure 7. (A) Concept board from workshop A #1 (with *Morphino*); (B) Concept board from workshop A #2 (without *Morphino*).

Categories of generated ideas

We assigned each idea to one or more *MorphUI* categories (Table 3), where there were clear morphing mechanism(s) in the description or title of the idea. The most popular categories of shape-change were *Inflatable* and *Foldable*, which corroborates the findings in [87], where the authors highlighted these as the most popular categories of shape-change in HCI literature. This indicates that, in general, the participants tended to steer towards concepts that they were already familiar with.

MorphUI category	A #1	B #1	A #2	B #2
Elastomers	5	3	1	1
Auxetic	3	0	0	2
Rollable	2	1	1	5
Foldable	3	12	4	5
Inflatable	8	2	3	9
Anisotropic	0	0	1	1
Multi-stable	2	0	0	0
Shape memory	1	0	0	1
Undefined	*9*	*4*	*19*	*3*

Table 3. Categories of ideas generated in each workshop.

Workshop A #1, which used *Morphino* first, generated ideas across all categories except for *Anisotropic*. When the same participants took part in the workshop a week later (A #2), without the cards, most of their ideas were general and did not specify a form of shape-change; for example, the idea 'Normal height goes to standing desk to encourage movement' does not provide specific details of the shape-change, i.e., through unfolding of legs, or through a stretching or sliding mechanism, for example. In some cases, the participants remembered some of the principles on the nature cards from the previous workshop A #1, demonstrated, for example, by the idea '3D Display to show animal shape-change, e.g. peacock expands like a fan, puffer fish expands like a balloon' which have clear references back to the 'peacock train' and 'porcupinefish' cards.

Most of the ideas generated during workshop B #1, during which participants did not use the *Morphino* kit first, fell into the *Foldable* category. During the second workshop, B #2, when the participants were introduced to the *Morphino* kit, an increase in the number of ideas using *Auxetic*, *Anisotropic* and *Rollable* principles was seen. This suggests that *Morphino* encouraged participants to adopt forms of shape-change beyond those they already knew.

Use of the cards

In the workshops with *Morphino*, 25 out of 29 ideas were created using the cards in workshop A #1; one of those ideas – 'A toy swan: Origami toy for kids' – was based on the symbol of the *Foldable* mechanism on the card rather than the nature example itself; similarly, 'Wallet device: Semi-transparent or open on front?' was labelled as *Folding, Elastomers*, naming the shape-changing mechanisms on the cards rather than the example from nature. All of the ideas in workshop B #2 were based on examples from the cards. This indicates that the participants gravitated towards using the kit when it was available, whether that was through drawing inspiration from the organism on the card, or using the shape-change categories.

Table 4 details the number of times each *Morphino* card was used. The 'Octopus arms', 'Cuttlefish skin' and 'Cow udder' cards were used the most frequently (4-5 times each). Due to the many forms of shape-change an octopus arm can take (i.e. twisting, curling, stretching), it is unsurprising that this was the most popular card used in the workshops. While 'Cow udder' and 'Cuttlefish' are more unusual shape-change mechanisms, one possible explanation for their frequency of use could be the simplicity in the rotoscope design and how quickly users could grasp an understanding of the mechanism. Some cards, such as 'Bittercress siliques' and 'Wheat awns', were not used at all, likely due to the more complex and unfamiliar *Multistable* mechanism that these exhibit, and, given the duration of the workshop, may require more time to comprehend how this could be exploited in the design of SCIs.

Organism	#	Organism	#
Octopus arms	5	Human skin	1
Cow udder	4	Ladybird wings	1
Cuttlefish	4	Bat wings	1
Spider silk	3	Peacock train	1
Porcupinefish	3	Ice plant	1
Frigatebird	3	Pine cone	1
Walrus	3	Tree branches	1
Female cane toad	2	Venus flytrap	1
Three-banded armadillo	2	Sensitive plant	1
Golden wheel spider	2	Cucumber tendril	1
Butterfly proboscis	2		

Table 4. Number of times a *Morphino* card was used in the workshops.

Findings: From the workshop discussions

An analysis of workshop discussions provided insights into how the cards were used and how they affected creativity.

Impact of cards on idea generation

Some participants from both workshops admitted that initially they were sceptical as to whether the cards would provide any value, but were positively surprised by their usefulness:

> *"I think at first we started out with a few ideas that weren't on the cards and it felt at that point that I probably wouldn't use the cards. Then we went through the cards, looked at a card for a period, chatted about it and came up with a bunch of ideas from each card. Some cards that didn't work and some that really did."*

> *"The cards were surprisingly useful, in the sense that you think you've got a load of ideas to start with but as soon as you are running a bit dry, the cards really helped."*

The cards also helped participants to go beyond obvious changes in shape:

> *"I feel like without the cards I probably would have only done inflatable and folding stuff."*

> *"Also the spiders web, I probably wouldn't have thought about it in that context. I would have thought probably folding and inflatable, not stretching materials to that degree."*

The above decision to look at a spider's web for inspiration led to several unique ideas such as a temporary hammock that can be spooled out of a phone and used in a packed train, and an elastic net to secure (trap) luggage on a train or in a car boot.

Without the cards, participants reported relying on personal examples to help ideation (e.g. in the school scenario they remembered being a student). Some participants felt more free to ideate without the cards as they could come up with their own ideas, whilst others felt the opposite. This could be due to individual differences as some participants may be more used to ideating than others.

While the cards generally helped participants to develop new ideas, they sometimes introduced constraints. Participants felt the rotoscope was the most important part, but also reported that at times they would simply try to copy the shape-change mechanism described on the card and design a device that does exactly the same thing, but in a different context. For example, one group came up with an idea for a foldable origami swan toy, while another designed an octopus-inspired device that can be attached to a wall to mount a screen. However, others admitted that while they started with copy-cat ideas, this then led to more thoughtful discussions and more creative ideas:

> *"We only tried to fit the ideas at the start [...] but quite early on ii turned into the ideas coming from the cards rather than cards fitting the ideas."*

Nevertheless, all participants were confident in saying that the cards affected their creativity because they were the starting point of their thinking. They agreed that the session with cards was the most useful in generating novel ideas as it forced them to think outside of their comfort zone:

“[The cards] released my anxiety when starting: it frees [you] from the problem of a blank page. There is something to start from right at the beginning.”

“We saw things so weird in nature we felt free to have weird ideas.”

Not only did the cards inspire the participants, they also helped them to learn the framework on which they are based. Some participants mentioned that they learnt about the shape-change categories and discovered some they did not know about:

“Because there were some forms of shape-change that I did not know before I saw the card, it brought a sense of realism to what things can be done [...] I definitely learnt something, there were categories I did not know, and it influenced the idea of things I could do. The class of stuff would help me more generally.”

Using the cards

The method of using the cards differed between participants. Some spread the cards across the table, while others went through one by one. A few felt lost with so many cards (30). Some looked at the cards and read a few before ideating, which helped them “fill their mind with a lot of random things” that could then be combined before looking at the context. Participants mentioned that not all cards were appropriate for the given scenario and they sometimes tried to fit ideas to the cards. This led to a discussion on how ideation cards could restrict designers, although the participants acknowledged that the kit allows flexibility and if they started with a specific problem in mind (as opposed to the broad scenarios we provided), the cards could help them identify possible solutions:

“I found that there’s a lot of stimulation towards solutions, but then actually in terms of problems [...] there’s no really stimuli on that front.”

“I agree with the bottom-up vs. top-down thing [focusing on problems vs solutions]. It makes you think of solutions before you identify a problem [...] and this is the reverse of how I would tackle a design problem.”

“One good thing about not having the cards is that we thought more about the problem than the solution. I think [...] the card leads you into a solution first way [...] that may mean that the problems were less real with the cards, but the solution were less real without the cards.”

The procedure we proposed is flexible depending on whether the design team prioritises problems or solutions. A two-phase design process could also be used; first without the cards to better understand the scenario, and then add the cards later in the process. One participant mentioned that we could provide a library of deformable materials which could help participants connect with tangible properties of shape-change.

DISCUSSION & FUTURE WORK

The workshops demonstrated that *Morphino* was not only an inspiring resource for SCIs, but it also helped participants move beyond typical foldable and inflatable mechanisms frequently used in HCI and consider new forms of shape-change from other fields. While the participants tended to steer towards familiar concepts, they also commented that they learnt about forms of shape-change previously unknown to them. For some participants, the cards left a lasting impact, since a collection of ideas referred back to the cards and their mechanisms, even when the cards were no longer available to use. This highlights how *Morphino* has helped to further bridge the fields of HCI and material science. The next step would require participants to use technologies from the online database [87] and attempt to turn their ideas into physical prototypes.

Using the nature examples on the cards led to participants feeling more ‘free’ in generating ideas outside of typical shape-change in HCI. While they felt that not all the cards were appropriate for the design scenarios given, they concurred that *Morphino* provided an starting point for their thinking and forced them to think of ideas outside of their comfort zone. Nature has already proved to be a source of inspiration in other fields and we believe that bioinspiration can also be beneficial to the HCI community. Behind the field of SCIs is the concept of Organic User Interfaces (OUIs), which originated with the desire to adopt natural forms to design a better fit with human ecology [52]. In [51] the authors highlight how nature can inspire the design of flexible and adaptable shapes for interactive displays to improve usability and affordance. We hope that our work can inspire new research in this direction.

Compared to existing toolkits, in *Morphino*, we have successfully created a transfer-application tool that links a taxonomy of shape-change to an existing database of implementation, *MorphUI*. While transfer-application tools exist in other design spaces, this is the first of its kind specifically for SCIs. Additional workshops with different participant groups, such as UX and product designers, will aid in refining the toolkit. Furthermore, the cards could also be expanded beyond SCIs to include other forms of bioinspired design for the development of new interaction techniques outside of shape-change.

CONCLUSION

While instances of bioinspired design exist in HCI, the many examples in other fields illustrate that bioinspiration has the potential to support divergent thinking and the exploration of design spaces. Our goal with *Morphino* was to provide a nature-inspired resource for new design ideas for SCIs and address one of the main challenges in supporting such activities, by developing a tool to enable designers to transpose ideas into real-life prototypes. We achieved this by linking *Morphino* to an existing database of research. The results from our workshops demonstrate that, in addition to helping users generate ideas outside of typical HCI shape-change (i.e. foldable, inflatable), *Morphino* improved the awareness of shape-change mechanisms from material science, establishing it as another successful step in improving the synergy between these fields.

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