Metaphoraction: Support Gesture-based Interaction Design with Metaphorical Meanings

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Previous user experience research emphasizes meaning in interaction design beyond conventional interactive gestures. However, existing exemplars that successfully reify abstract meanings through interactions are usually case-specific, and it is currently unclear how to systematically create or extend meanings for general gesture-based interactions. We present Metaphoraction, a creativity support tool that formulates design ideas for gesture-based interactions to show metaphorical meanings with four interconnected components: *gesture*, *action*, *object*, and *meaning*. To represent the interaction design ideas with these four components, Metaphoraction links interactive gestures to actions based on the similarity of appearances, movements, and experiences; relates actions to objects by applying the immediate association; bridges objects and meanings by leveraging the metaphor TARGET-SOURCE mappings. We build a dataset containing 588,770 unique design idea candidates through surveying related research and conducting two crowdsourced studies to support meaningful gesture-based interaction design ideation. Five design experts validate that Metaphoraction can effectively support creativity and productivity during the ideation process. The paper concludes by presenting insights into meaningful gesture-based interaction design and discussing potential future uses of the tool.

CCS Concepts: • **Human-centered computing → Interaction design**; **Systems and tools for interaction design**; *Interaction design theory, concepts and paradigms.*

Additional Key Words and Phrases: Gesture-based Interaction Design; Creative Support Tool; Metaphor; Mobile Gesture; Wearable Gesture; User Experience

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1 INTRODUCTION

The interest in incorporating a wide range of human skills and abilities in interaction design diversifies the user experience of computation [95]. With the availability of advanced sensory solutions, the development of gesture-based interaction techniques enables designers to create computing interfaces and interactive mechanisms with which users are familiar [39]. For example, popular applications turn mobile devices into musical instruments, like a flute [129], a guitar [2] or a violin [51], that can be performed by "blowing" (Figure 1.a), "strumming" (Figure 1.b) or "playing" (Figure 1.c). These designs familiarize users with novel interactive content by directly applying everyday gestures to the represented objects instead of conventional mobile interactions (*e.g.*, tapping). To further augment such forms of technological practices, previous research [*e.g.*, 24, 93]

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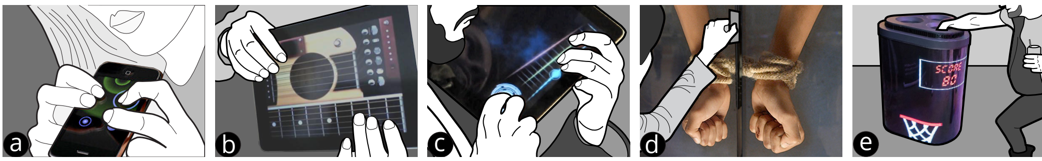

Figure 1. Examples of the gesture-based interaction design: (a) *Ocarina* [129] (© Smule, Inc.); (b) *GuitarPad* [2](© AccpleMind); (c) *Magic Fiddle* [51](© Smule, Inc.); (d) *Social Swipe* [112](© Kolle Rebbe GmbH); and (e) *TetraBIN* [138](© Sencity).

has studied how to design rich interactions that are direct and consistent with user behavior and particularly emphasized how to affect users' thoughts and actions through the design.

An emerging trend of recent Human-Computer Interaction (HCI) research showcases that gesture-based interaction designs allow users to encounter, interpret, and sustain abstract meanings [6, 99, 135], which cannot be directly experienced through the human senses [157]. Referring to the previous literature [99, 123], we emphasize that "meaning" here is the information intended to communicate but not be expressed or represented directly, and "meaningfulness" as the quality of sense-making and the degree of coherence based on one's experiences at a comprehension-level. Such explorations open up an opportunity to convey abstract concepts or information through human actions and interactive experiences [16, 115]. For instance, *Social Swipe* [112] is a digital advertising poster that implements gesture-based interactions with a persuasive call to action. By swiping credit cards through a specially designed kiosk screen, the "swipe" gesture activates a video, which translates "swiping card" into "slicing bread" or "cutting rope" (Figure 1.d). Such interactions demonstrate that the abstract meaning of "help" or "freedom" illustrates to users how their donation to the German charity *Misereor* will benefit those who are in need. As another example, *TetraBIN* [138] augments users' waste disposal behaviors through LED screens on the receptacle. The content (*e.g.,* a basketball scoring board or the *Tetris* game) projected on the screen remind people about the "shooting ball" (Figure 1.e) or "releasing block" scene when they "drop" the litter into the trash bin. Such designs reflect the concept of "achievement", which communicates to users that their behavior in promoting environmental protection is rewarded. These examples reflect that gesture-based interactions, when intimately connecting with the settings in which it occurs, can play a role in revealing abstract meanings through our daily activities. Nevertheless, the specialized hardware configurations and ad-hoc design decisions remain bottlenecks when applying such designs to a broad spectrum of interactive applications.

Making abstract concepts accessible and intuitive is the key to creating meanings through gesture-based interactions during the ideation process [66]. Thus, it is an essential task for designers to shape meaning through interactive products [65]. However, how to systematically design gesture-based interactions augmented with a meaningful experience on mobile and wearable devices is still underexplored. On the one hand, it is unclear what kind of gesture-based interactions are readily deployable with sensors available in the market. For one thing, conventional mobile/wearable interaction designs have focused on utility and usability with interface elements or graphical widgets, and it is unsure what gestures can be transformed and remain accessible in a daily life scenario. For another, existing exemplars with novel interactive techniques used to be domain-specific or designed in an ad-hoc manner. Therefore, design ideas may fail to be implemented if designers ignore the hardware restrictions during the ideation process [21, 63]. On the other hand, creating gesture-based interactions with abstract meanings is not a trivial task for designers. Previous research shows that metaphors dominate human conceptualization processes [83] and allow designers to parallel unrelated entities by fostering their imaginations and facilitating moments of inspiration [156]. Hence, we could leverage metaphors to manifest the coupling between "what is done" and "what is meant" [36]. When representing abstract meanings, it is uncertain which metaphors make sense and are meaningful to general audiences, and there also seems to be limitless design possibilities [119]. It is thus beneficial to take a systematic approach to guiding designers through the exploration of a gesture-based interaction design with metaphorical meaning at the ideation stage.

In this work, we aim to examine the application of metaphor in interaction design ideation. Our goal is to help designers systematically explore and formulate design ideas that express abstract meanings through gesture-based interactions. To achieve this goal, we propose Metaphoraction, a creativity support tool that generates design idea candidates based on designers' input. Through decoding gesture-based interactions into motor movements and physical manifestations within interactive processes [56], we describe the pipeline of Metaphoraction across four interconnected components – *gesture*, *action*, *object*, and *meaning* – in the scope of this paper. These four components are extracted by analyzing existing design exemplars (*e.g., Social Swipe*). Considering the multiple choices of potential interactive gestures, we focus on general upper-body interactions with mobile and wearable devices, which could be extended with future emerging techniques or other interactive platforms. Based on this conceptualization, we construct Metaphoraction by addressing four research questions (**RQ**) through a series of research activities.

- First, we explore "**RQ1** – What are the common upper-body interactive gestures supported by existing mobile/wearable technologies?" by conducting a comprehensive literature survey on common mobile and wearable gestures to obtain readily developed interactions or those with minor adaptations.
- Next, after obtaining potential gestures, we identify "**RQ2** – What are the corresponding actions and associated objects when mapping the gestures to the physical world?" through a crowdsourced study to collect users' understanding of the surveyed gestures.
- Then, we investigate "**RQ3** – What are the widely accepted meanings extending from the objects based on the metaphor TARGET-SOURCE[1] pairs in the semantic space?" by inferring the meaningfulness of metaphors from the crowd data to convey higher-level, abstract meanings based on the objects derived from the second step.
- Finally, we are interested to know "**RQ4** – How would designers use Metaphoraction in various design tasks during the ideation process?" by holding a design workshop with five design experts and conducting semi-structured interviews to openly explore their feedback of the tool and ideation experiences.

The final output of Metaphoraction is a broad set of *gesture-action-object-meaning* design idea candidates that improve designers' creativity and productivity. These candidates illustrate how users may interpret the metaphorical meanings of a gestural interaction when performed in the physical world. We develop a web application prototype for Metaphoraction and conduct a design workshop with a professional design team to explore its uses in ideating gesture-based interactions for mobile advertisements. Qualitative feedback from the design experts shows that Metaphoraction facilitates the generative design process with idea exploration, iteration, and validation. The key contributions of this paper are threefold:

(1) we propose a solution to facilitate the systematic ideation for gesture-based interactions representing metaphorical meanings;

[1]In this paper, TARGET denotes the target domain and SOURCE denotes the source domain.

(2) we conduct a survey and two crowdsourced studies to implement a creativity support tool, Metaphoraction, with 588,770 unique design idea candidates for mobile and wearable interaction designs; and
(3) we evaluate our tool with a design team from a local company to demonstrate its ability to support creativity and productivity in meaningful gesture-based interaction ideation.

2 BACKGROUND

2.1 Design Interactions with Metaphors

The traditional understanding of metaphor use in HCI is widely associated with graphical user interface design (*e.g.,* the desktop metaphor) [102]. However, the metaphor also plays an influential role within the interaction design process in the HCI community [118], as it is helpful to understand new concepts and generate new ideas on familiar objects by providing cues. Generally, the use of metaphors is widely recognized as "a process of reification" to make abstract ideas or phenomena concrete, but its creative potential also makes metaphors "function as a creative tool for the designer" [19]. First, when serving as a communication channel, metaphors enable users to establish an effective mental model for the rapid transfer of input information to knowledge that they have acquired [83, 141]. For example, Mahut *et al.* [94] formalized the relationship between user experience, interaction, and metaphors. The authors presented a taxonomy to understand interactive products' physical and digital properties by integrating the notion of metaphor. Second, when employed as a strategy for creative design, metaphors help designers achieve inspiring innovation and creative intuition [102]. By taking the *desktop metaphor* as an example, Blackwell [19] investigated the use of metaphors for future HCI research and design discipline, where scholars have reified creative experience as a conceptual blend of computation domains and everyday life.

Moreover, Hurtienne *et al.* [66] proposed to use primary metaphors – "a conceptual association of an image schema with an abstract target domain" – as a source of design guidance for gesture interaction on mobile multi-touch devices. They provided guidelines by examining the relations between gestural interaction and abstract interactive content based on primary metaphors. In this work, we treat metaphors as a tool to facilitate the reification of interaction design ideas by referring to familiar interactive experiences. In particular, we are interested in the creative potential of metaphors when introduced to designers during the ideation process. Metaphors are and will remain a rich and complex topic space in HCI, but in the scope of this paper, we adopt a single basic formulation for practical purposes; that is, metaphors constitute mapping concepts from source domains to target domains [83]. This formulation is consistent with human mental processing when interpreting ontological correspondences applied in metaphors [*e.g.*, 19, 89, 141]. Based on the formulation, this work explores how to assist designers in ideating the expression of abstract meanings by deriving gesture-based interactions associated with concrete objects connected to these meanings by metaphors.

2.2 Creativity Support for Design Ideation

Creativity support tools enable designers "to express themselves creatively" and empower users "to be more productive" in one or more "distinct phases of the creative process" [41, 114, 128]. Previous works [41, 144] reviewed creativity support systems and analyzed them according to the various stages of a creative process, such as pre-ideation/background research, idea generation or ideation, evaluation or critique, implementation, iteration, and meta or project management. This paper focuses on facilitating designers to formulate ideas with potential candidates based on the enumerated instances in the ideation phase.

There is a wide diversity of creativity support tools in HCI [41], and previous research has proposed multiple methods to support the ideation processes with experimental prototypes. To name a few, Müller-Wienbergen *et al.* [101] provided multiple types of stimuli on a browsing window to evoke ideas, allow induction, and cater to different creative styles. Althuizen and Wierenga [4] provided a case-based reasoning system and supported creative problem-solving with existing successful exemplars. MacCrimmon and Wagner [92] studied how to generate creative alternatives for ideation by connecting internal problem components with the external environment and elements. In addition to supporting different ideation strategies, existing works also explored varied representations of ideas. Faste and Lin [40] used an idea generation technique – mind maps – for idea generation. *Spinneret* [14] also adopted mind mapping to enable the exploration of non-obvious concept associations for creative ideation. Similarly, MetaMap [70] utilized a mind-map-like structure to recommend example materials and inspire users to explore divergent idea space. Other studies, such as Garfield *et al.* [43], leveraged groupware-based creativity techniques to facilitate the ideation process with novel ideas. An existing web application, *IdeaMâché* [80], supports curation and presentation with a composition of user collected information on a mood board. Inspired by these works, we present Metaphoraction with potential design idea candidates in a manner of mind mapping, connecting major components of meaningful gesture-based interactions based on collected crowdsourcing data to catalyze ideation activities interactively.

Due to the lack of a unanimously adopted definition of creativity, evaluating the creativity support tool has been particularly challenging [26]. Inspired by NASA Task Load Index [55], Cherry and Latulipe [29] developed a pioneering metric – Creativity Support Index – to quantitatively measure six dimensions (*i.e.*, exploration, expressiveness, immersion, enjoyment, results worth effort, and collaboration) of creativity support based on creativity research theories. Kerne *et al.* [73] also introduced metrics of curation to evaluate information-based ideation support tools, including elemental and holistic ideation metrics. Since there is a lack of proper baseline tools that could provide similar support as Metaphoraction, we focus on the qualitative evaluation and design our interview questionnaires by borrowing these criteria. Our goal is to obtain an in-depth understanding of how designers would use Metaphoraction during the ideation.

3 OVERVIEW

3.1 The Components of Metaphoraction

Previous works have demonstrated successful cases to represent abstract meanings through gesture-based interactions [112, 134], but designers mostly designed such interactions on a case-by-case basis and give anecdotal evidence to make the interactive processes meaningful. When making the gesture-based interaction design with extended meaning scalable, it is crucial to understand how likely users would conceptualize those abstract meanings of the interactive content with the

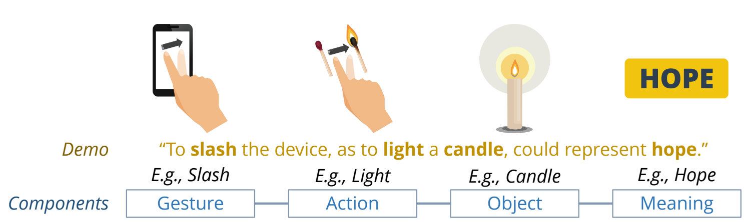

Figure 2. An overview of Metaphoraction construction with four components: *gesture*, *action*, *object*, and *meaning*.

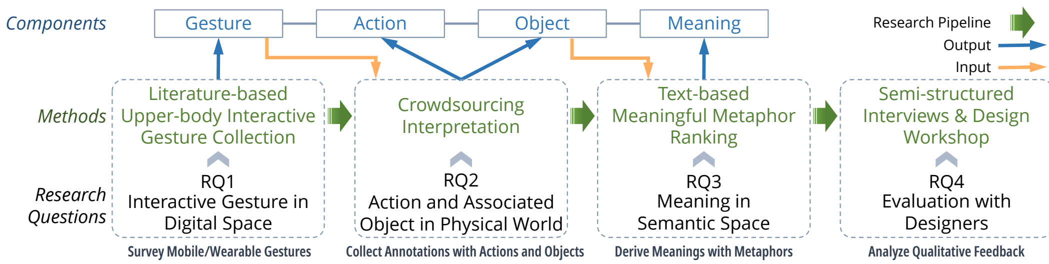

Figure 3. An overall research pipeline of Metaphoraction.

corresponding gesture operated on a digital device in real life. As a result, it is preferable to have a tool that can formulate design ideas between digital interactions and conveyable meanings. To this end, we leverage metaphor – not merely a rhetorical technique but rather a profound element of communication and thought [16, 83] – to enable the parallel of unrelated concepts [83], understand novel and complex phenomena [156], and foster divergent and creative thinking [19, 49]. We present Metaphoraction, which applies direct association and figurative language as proxies for connecting digital technology, the physical world, and semantic space. As shown in Figure 2, the design idea candidates generated by Metaphoraction consist of four interconnected components: *gesture*, *action*, *object*, and *meaning*. Specifically, we define:

(1) *Gesture*: an operation people perform to activate functions or effects in a digital system;
(2) *Action*: a process or movement to achieve a particular thing in everyday life;
(3) *Object*: a thing to which a specified action is directed; and
(4) *Meaning*: a message that is intended, expressed, or signified.

The meaning, which extends or amplifies the represented context, is achieved through the metaphorical association between users' lived experience and prior knowledge based on the presented interface and interaction design.

Through these four components, Metaphoraction aims to

(1) render digital interactive gestures into daily actions based on their similarities in appearance, movement, and experience,
(2) link actions to objects according to frequent associations; and
(3) connect concrete objects to more abstract, higher-level meanings through the TARGET-SOURCE mapping in the metaphors.

Its ultimate goal is to support the generative ideation [40, 67] of a gesture-based interaction design with metaphorical meanings, while achieving both creativity and productivity [17, 58, 114] in the ideation process. To this end, Metaphoraction aims to assist designers in interactively exploring and comparing possible design idea alternatives as well as constructing and validating plausible design ideas based on the given context.

3.2 Research Methodology

To realize the qualities mentioned above, we develop Metaphoraction according to those four components through a series of activities (Figure 3).

(1) We conduct a literature survey to compile a list of 52 widely accepted, lightweight interactive gestures supported by commercially available devices or off-the-shelf wearable/mobile sensors. We code each gesture in terms of the source, supported device, available sensors or algorithms to assist in searching for proper interactions based on the context of use.

(2) We carry out a crowdsourced study to translate every given interactive gesture into a set of daily actions performed on associated objects by removing the presence of the digital system. We encourage a diverse interpretation from the crowd and include synonymous words to expand the collection of actions and objects. We also use the frequency of occurrence to indicate popularity and the ranking to represent the level of meaningfulness and facilitate the screening process.
(3) We exploit a large metaphor dataset mined from web resources [89] to infer possible messages conveyed from the objects into meanings. Those meanings provide the contextual information for each object identified in the crowdsourced study when those objects are used as SOURCEs in metaphors. We build a supervised machine learning model to learn what types of *object-meaning* pairs people find meaningful based on crowdsourced workers' assessments.
(4) We validate the interface design of Metaphoraction with 26 university students with design backgrounds and conduct a design workshop with five design experts from a local company. We collect all the participants' feedback through semi-structured interviews to obtain a deep understanding of their ideation experiences. We further perform qualitative analysis on experts' interview transcripts to derive the potential usage of Metaphoraction and some design considerations for meaningful interaction.

Following this pipeline, we detail these activities to build Metaphoraction's back-end in the following Sections 4, 5, and 6, respectively. We further describe the interface design process and implementation details in Section 7 and the evaluation procedures and results in Section 8. We discuss our findings in Section 9.

4 SURVEY COMMON MOBILE AND WEARABLE GESTURES

To tackle RQ1, we collect interactive gestures through a literature survey on common mobile and wearable interactions, while focusing on the widely accepted interactions supported by available mobile and wearable sensors in people's everyday lives. The survey goal is to capture a collection of upper-body interactive gestures through a systematic review of state-of-the-art gesture design works in the HCI field. Following the adapted Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [100], we report the review process following the four main phases in Figure 4.

4.1 Gesture Survey: Relevant Research Entries Identification

4.1.1 Source selection. We focus our research on the top 20 HCI journals and conferences ranked by Google Scholar Metrics [122] (*i.e.,* CHI, CSCW, UbiComp, UIST, TOAC, IJHCS, TOCHI, HRI, BIT, TOHMS, ICMI, IJHCI, IUI, TOH, HCI International, TEI, DIS, Mobile HCI, IDC, the journal of CSCW). We exclude HRI because of its weak relevance to the scope of our work. Instead, we include the IMWUT due to its relevance to HCI and the scope of our review. We identify and collect relevant literature from six mainstream electronic databases, *i.e.,* ACM Digital Library, IEEEXplore, Taylor & Francis Online, Springer (Link), Elsevier (ScienceDirect), and Google Scholar Search Engine, while we further refine the results for all online sources by setting the period between 2009 and 2019. We set 2009 as the starting year because it is the year that affordable interaction infrastructures and devices started to emerge [77].

4.1.2 Eligibility criteria and search queries. For inclusion, we search for articles that present interactive techniques supported with mobile or wearable sensors without any extra accessories; moreover, the interactive gestures should perform the digital content pervasively for general users. To clarify the survey scope, we first define the *upper-body interactive gesture* as lightweight activities performed by the user's upper body when responding to the effect designed in the digital content. To

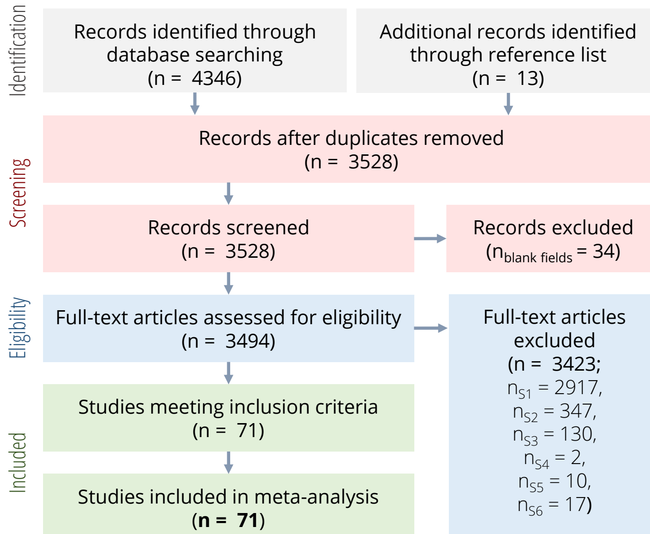

Figure 4. Adapted PRISMA flowchart of the survey selection process.

this end, entries should include the demonstration/explanation of proposed interactive gestures or provide adequate information on the interactive process employed. We explore previous literature results with two groups of combined key terms: (1) the first group of keywords being "mobile interaction" *or* "wearable interaction" and "elicitation" *or* "user-defined interaction" *or* "empirical study". This group of returned results presents the proposed interactive methods which general users are familiar or comfortable with; (2) from a broader perspective, the second group of keywords are "mobile interaction" *or* "wearable interaction" and "gesture", which covers available sensors with the proposed widely adopted interactions. We use a total of eight phrases as queries and obtain the research result lists from the six digital libraries through a local institution's subscription.

4.1.3 Data collection and screening process. Two researchers (one is with an HCI background while the other one majors in electrical engineering) carry out the study selection separately with the eligibility assessment in a standardized manner. We examine the first 100 search outcomes (if available) from each library for further review, as we gradually observe that several returned search results are less relevant to our goal after the first 100. We log the search results in an excel file by removing entries with duplicated titles, unavailable sources, or blank fields (*i.e.,* missing the title, keywords, or the conference name partially or entirely).

To start with the screening (S) of the full-text articles, we first (S1) remove publications that are not included in the journal and conference list; and we also exclude the doctoral consortium paper from the survey pool. Then we (S2) rule out articles whose topics/content are unrelated to gesture (*e.g.,* user interface design, bias measurement), (S3) remove entries that are out of the scope of the device and interaction (*e.g.,* a large public display, whole-body interaction), and (S4) delete papers which neither present clear definitions/demonstrations nor further explain the given gestures by citing references. (S5) Articles discussing related techniques applied in digital content design with specific purposes or limited usage scenarios (*e.g.,* typing accuracy) are excluded. Finally, to ensure the technical feasibility of the selected gestures, we (S6) delete the papers without any demonstration of hardware implementation (*e.g.,* pure brainstorm or qualitative study). After getting an initial set of papers, we obtain 13 additional papers relevant to the target topic by following the snowballing method in systematic reviews [151].

In the end, 71 articles are left for further analysis after the exclusion. The inter-rater reliability shows that there is substantial agreement between the two researchers' judgments with Cohen's $\kappa = .78$ (95% confidence interval from .74 to .82), $p < .001$. Those disagreements have been resolved through discussion. The final survey pool includes 71 papers for further analysis after the overall eligibility assessment.

4.2 Gesture Survey: Results and Analysis

After obtaining the 71 potential publications on interactive gesture design, we code the presented gestures, which are user-friendly, feasible for implementation, and commonly used across mobile and wearable devices from the sample articles. We exclude the interactive gestures that draw predefined symbols during the coding, as these symbols are depictions of certain semantic meanings and usually case-specific or culture-related (*e.g.*, drawing a cross mark to represent the "cancel" command). Then we categorize those that share similar gesture trajectories and achieve the same effect in one item regardless of the gesture type or required sensors for the remaining gestures. Through an independent coding process, there are a total of 52 distinct gestures that are finally selected. To assess the inter-rater reliability, we run Cohen's κ to determine if there is an agreement between two coders' judgments of identifying the gestures which fulfill the requirements mentioned

Table 1. The survey results of 52 common mobile/wearable interactive gestures are grouped based on their trajectories. Names in the "()" are other alternatives used in the surveyed paper. Notes in the "[]" of the **Name** column indicate the difference when performing the gestures which share the same name.

Name	Citations	Name	Citations
Dwell (Touch and hold, Long press)	[60, 64, 82, 87, 96, 104, 107, 108, 131]	Bend [single hand]	[7, 37, 113, 136]
Wave (Wiggle)	[10, 148]	Hover	[50, 53, 153, 159]
Hinge	[78]	Circle (Lasso, Draw a circle)	[9, 27, 45, 46, 50, 60, 61, 88, 90, 96, 124, 126, 131, 132, 145, 149]
Swing (Pitch, Sway)	[5, 15, 117]	Pinch	[3, 9–11, 42, 48, 52, 53, 64, 68, 69, 75, 82, 86, 88, 90, 107, 121, 124, 130, 145, 147, 148, 158]
Touch	[9, 97, 108]	Splay (Stretch, Spread, Expand, Open, Zoom) [palm up]	[32, 68, 75, 126, 130, 140, 158]
Move	[10, 32]	Strike (Beat)	[52, 85, 104]
Scroll (Flick, Slide)	[3, 28, 35, 44, 61, 64, 85, 90, 96, 107, 140, 154]	Drag (Pull, Pan)	[3, 11, 20, 46, 53, 64, 69, 85, 87, 90, 107, 124, 126, 130, 152]
Squeeze (Grip, Grab, Grasp)	[59, 113]	Cover (Cradle)	[9, 108]
Tap (Press)	[3, 7, 9, 20, 27, 35, 42, 44, 46, 48, 52, 53, 59–61, 64, 68, 69, 85–88, 90, 96, 104, 107, 113, 121, 124–126, 133, 139, 147, 148, 152, 154, 159]	Scratch (Scribble, Rub)	[59, 125]
Raise and down	[78, 133, 145]	Rotate (Tilt, Pan, Yaw, Turn) [single hand]	[9, 10, 15, 28, 33, 48, 64, 76, 78, 79, 82, 117, 124, 133, 139, 140, 147, 152]
Point (Poke, Push)	[75, 77]	Palm hold	[145]
Fist (Punch)	[10]	Swipe (Fling, Swing)	[9, 27, 28, 35, 48, 60, 61, 64, 68, 78, 82, 85, 90, 96, 104, 108, 113, 124, 126, 130, 131, 145, 149, 150, 153, 159]
Clap	[52, 86]	Brush away	[11, 32, 68, 75, 90, 130, 140, 158]
Back slap	[86]	Head circle	[155]
Make it rain	[86]	Splay (Stretch, Spread, Expand, Open, Zoom) [palm down]	[11, 32, 68, 90, 140, 158]
Shake	[5, 64, 68, 76, 108, 117, 125, 152]	Palm rub	[86]
Knock	[125]	Type	[52, 85, 104]
Sweep (Shear)	[78, 147]	Double tap	[42, 64, 82, 96, 107, 126]
Bump	[86]	Nod	[155]
Bring hand to mouth	[76, 117]	Blow (Puff)	[28]
Head shake	[155]	Snap	[52, 86]
Accelerate	[76, 79, 117]	Bend (Fold) [double hand]	[37, 74, 81, 113]
Twist	[7, 74]	Rotate (Tilt, Pan, Yaw, Turn) [double hand]	[28, 64, 79, 139, 152]
Flip (Facedown, Roll)	[15, 59, 76, 82, 116, 117]	Finger slide	[45, 52, 86, 145, 148]
Flex	[9, 33, 52, 86, 150, 158]	Crumble	[7]
Place hand to ear	[76, 117]	Palm tilt	[145]

Table 2. The annotation for 52 common mobile/wearable interactive gestures with their type and available sensor categorization is identified from previous research. In the **Type** column, "T" represents touch-based interactive gestures; "V" represents vision-based interactive gestures; "D" represents device-based interactive gestures. In the **Sensor Categorization** column, "1" represents the video camera; "2" represents the infrared 3D camera; "3" represents the capture system for mid-air gestures; "4" represents the wearable sensors; "5" represents the touch-sensing system for surface gestures; "6" represents the microphone; "7" represents other sensors which the authors specially design. The ordering of the gestures follows Table 1.

Gesture Name	Type			Sensor Categorization						
	T	V	D	1	2	3	4	5	6	7
Dwell	■				■		■	■		■
Wave		■			■		■			
Hinge		■			■					
Swing			■				■			■
Touch			■		■		■	■		
Move		■			■	■				
Scroll	■			■				■	■	■
Squeeze			■				■	■		
Tap	■	■		■	■	■	■	■	■	■
Raise and down		■	■		■	■	■			■
Point		■			■					■
Fist		■			■					
Clap		■					■		■	
Back slap		■					■			
Make it rain		■					■			
Shake			■				■	■		■
Knock			■					■		
Sweep	■	■			■			■		
Bump		■					■			
Bring hand to mouth		■					■			■
Head shake		■								■
Accelerate			■				■			■
Twist			■					■		
Flip			■				■	■		■
Flex		■			■		■		■	■
Place hand to ear		■					■			■
Bend [single hand]			■					■		
Hover		■		■	■					■
Circle	■	■		■	■	■	■	■		■
Pinch	■	■		■	■	■	■	■	■	■
Splay [palm up]	■	■		■	■	■				■
Strike	■								■	■
Drag	■	■		■	■		■	■		■
Cover		■			■		■	■		
Scratch	■	■					■	■		
Rotate [single hand]	■	■	■	■	■	■	■	■	■	■
Palm hold		■				■				
Swipe	■	■		■	■	■	■	■	■	■
Brush away		■		■	■	■				■
Head circle		■								■
Splay [palm down]	■	■		■	■	■				■
Palm rub	■	■					■			
Type		■							■	■
Double tap	■			■				■		■
Nod		■								■
Blow		■							■	
Snap		■					■		■	
Bend [double hand]			■					■		
Rotate [double hand]	■		■			■	■	■		■
Finger slide		■				■	■	■	■	
Crumble			■					■		
Palm tilt		■				■				

above and the screening criteria. There is near-perfect agreement between the two researchers' judgments, $\kappa = .98$ (95% confidence interval from .96 to .99), $p < .001$. Two researchers resolve the disagreement through discussion before merging the results. After combining records that describe the same gesture under different names, we obtain a final list of 52 unique interactive gestures (Table 1). This paper refers to the gestures by the most common names used in the literature we have surveyed.

4.2.1 Interactive gestures. According to the gestures' action space and applied objects when executed in real settings, we divide the 52 representative gestures into three categories [13, 103, 109, 111] (Table 2):

(1) **D**evice-based interactive gestures ($N = 13, 25.00\%$): mainly include motion gestures which are "deliberate movements of the device by end-users to invoke commands" [117] and leverage the traceability and mobility of hand-held devices, *e.g.*, shaking, tilting, and so on;
(2) **T**ouch-based interactive gestures ($N = 16, 30.77\%$): mainly include gestures that directly manipulate the virtual objects through surface computing technologies, *e.g.*, touching, dragging, and so on;
(3) **V**ision-based interactive gestures ($N = 37, 71.15\%$): mainly include mid-air gestures that involve the use of multi-finger, whole-hand shape, or body movement to express the operation intentions, *e.g.*, head rotating, palm tilting, and the like.

Note that some of the gestures may overlap because they share a similar interactive experience or same movement trajectory.

4.2.2 Involved body parts. Only hands and heads are involved in the collective of 52 upper-body gestures. There are a total of 6 (11.54%) gestures supporting head interactions. The remaining interactive gestures are all performed by hand gestures: 35 (67.31%) gestures use a single hand, while 11 (21.15%) gestures use both hands.

4.2.3 Applied devices and equipped sensors. Within the survey scope, the most frequently used devices studied among the 71 papers are mobile phones ($N = 35, 49.30\%$). The other platforms include smartwatches ($N = 16, 22.54\%$), tablets ($N = 3, 4.23\%$), head-mounted displays/smart glasses ($N = 7, 9.86\%$), bracelets/rings/pendants ($N = 3, 4.23\%$) and mixed devices ($N = 7, 9.86\%$). Most solutions adopt off-the-shelf smart device's built-in sensors to capture the gesture data. We present the related sensor categories adapted from the categorization of Vuletic *et al.* [143] to each gesture item in Table 2.

5 COLLECT ANNOTATIONS WITH ACTIONS AND OBJECTS

We target RQ2 by collecting general users' interpretations of common interactive gestures performed in daily life settings. Referring to the touchless gestural interfaces [47], we conduct an online user study to collect users' feedback based on the previously built gesture dataset. The study aims to understand how people map digital interactive gestures onto physical world actions and the immediately associated objects.

5.1 Action and Object Collection: Study Design

To identify how people interpret gestures adopted for digital device interactions and explore what the immediately associated target objects and underlying intentions are, we design a crowdsourcing task to collect the possible action(s), target object(s), and the underlying intention(s) from general users. In the study, we propose three questions for each gesture, targeting three aspects (*i.e., action*, *object*, and *intention*) respectively: (1) What *action* in daily life does this gesture remind you of? (2) What *object* may you likely apply this *action* to? and (3) What is your *intention* when performing this *action*? We aim to collect participants' answers on *action* and *object* components through the first two questions and validate those answers through the third question to avoid meaningless or case-specific feedback.

5.2 Action and Object Collection: Procedure

First, we record demonstration videos for each interactive gesture and then convert them to animated GIFs as the source material for this study. To allow annotators to fully understand how to perform those interactive gestures, we record all the gestures from the front and side views and align the corresponding frame according to the timeline. We also remove any restrictions (*e.g.,* context, device) when performing interactive gestures so that annotators can freely explore gesture usage scenarios [47].

We then implement a web interface based on the dataset. As shown in Figure 5, each gesture is displayed with two views on the left-hand side, and the aforementioned three questions (per case) are shown on the right-hand side. Before the study, we design an instruction page to demonstrate how to answer the questions regarding the assigned gesture. Each Human Intelligence Task (HIT) includes four different gestures, and each participant needs to provide at least three different cases for each gesture to diversify the responses [142]. We encourage all participants to come up with as many potential cases as they can. Upon acceptance of the submitted results, we provide a bonus to those with additional answers. All 52 gestures are randomly ordered, and there are no apparent differences between each action regarding task difficulty. We adopt the Latin square to assign a task to each participant in the study.

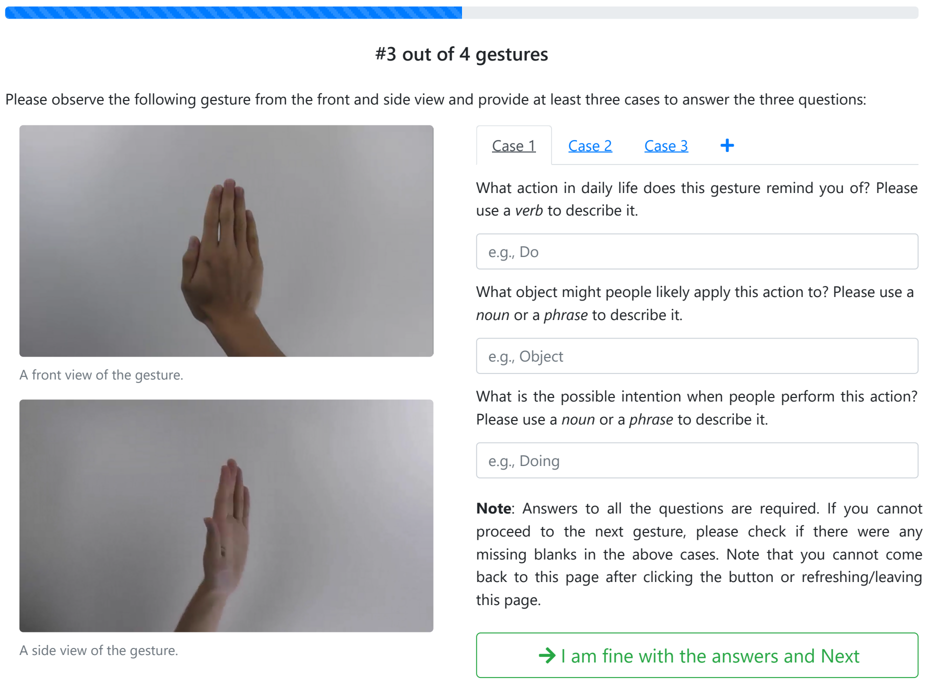

Figure 5. The user interface of the gesture annotation MTurk study. The screenshot shows the questionnaire page of the "Flip" gesture with example questions and animated GIFs.

We post the study online and recruit participants through Amazon Mechanical Turk (MTurk)[2]. During the study, we restrict the area to within the USA to ensure all participants use English as their first language so as to reduce any language bias. We also require them to have an overall HIT approval rate (across all HITs on MTurk) greater than or equal to 90% before participation.

5.3 Action and Object Collection: Results and Analysis

At the end of the study, 219 out of 334 unique workers participating in this study get approved (approval rate = 65.57%). Each worker's task costs 14.98 minutes on average, and every worker who provides valid feedback is rewarded with $1.50. We pay a bonus to 16 workers for providing inspiring answers with extra cases. Following the previous practice [142], we make sure that at least 15 unique workers contribute their annotations in three different cases for each gesture. There are a total of 4,036 valid answers in our collected data. To further clean the collected raw data, we first remove all punctuation using regex in the response and restore all verbs (to present tense) and nouns (to singular form) to their original state via *WordNet* of *NLTK* [91]. We then attempt to extract pure verbs and nouns from the answers of *action* and *object* questions, respectively. For terms with multiple meanings (*e.g.,* "beat" can mean both "strike" and "defeat"), we determine their senses manually based on the workers' original intentions collected in the third question. We also refer to the answers to the third question to possible worker intentions behind their possibly diverse feedback on these interactive gestures.

[2]Amazon Mechanical Turk: https://www.mturk.com/

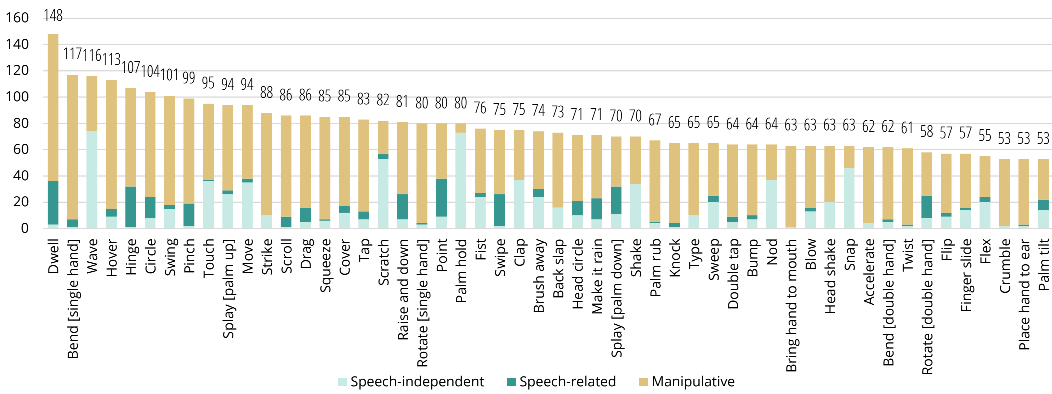

Figure 6. The distribution of the *actions* collected from the MTurk study. The X-axis is the *gesture* name adopted in Table 1. The Y-axis indicates the number of annotations, where the total number is marked at the top of each bar.

After cleaning the data, we collect 485 unique actions and 721 unique objects based on 52 interactive gestures. We group the gestures into communicative gestures and manipulative gestures through deductive coding [110, 143]. The communicative gestures are those used as a way to intensify or modify vocal speech or convey information through sign language [1, 110], while the manipulative gestures are produced to "control an object with the hands by acting directly on it in a real or virtual environment" [120]. The communicative gestures can be further categorized into speech-independent ("nonverbal acts that have a direct verbal translation or dictionary definition", *e.g.,* the symbolic) and speech-related ("used in parallel with verbal speech", *e.g.,* the deictic, iconic, metaphoric) gestures by following an existing taxonomy [38, 98, 143]. We present the distribution of collected results for each gesture in Figure 6. Most of the answers (70.73%) come under the manipulative gesture category by analyzing the crowdsourced data. This result suggests that users tend to treat mobile and wearable devices or things displayed on those devices as interactive objects that can be operated directly. From their answers, the top five annotations of the presented gestures obtained from crowdsourcing are "tap", "turn", "wipe", "grab", and "press". The speech-independent and speech-related gestures account for 20.85% and 8.42% for the communicative gestures, respectively. The top five speech-independent gesture annotations received from workers are "wave", "clap", "stop", "snap", and "high-five", while the top five speech-related gesture annotations are "mimic", "point", "show", "reveal", and "present".

Furthermore, we analyze the collected objects. Most target objects are physical stuff since the manipulative gestures account for the majority of the collected actions. The top five most frequently mentioned everyday things are "paper", "ball", "bug", "water", and "door". For the target objects which indicate living creatures, like "person", "animal", "friend", "child", "baby", and "pet", 84.69% of associated actions are communicative gestures. Specifically, we find the most used objects for deictic gestures (*e.g.,* "point") include "path", "map", "object" and "sign"; for iconic and metaphoric gestures (*e.g.,* "mimic") while popularly named objects included "firework", "firecracker", "shark", "butterfly" and "flower". We also find that the performer of the action may be an animal rather than a human, like the proposed *action-object* pairs of "wag – (dog) tail" and "wiggle – (fish/worm) body". The results indicate that a scenario setting, which provokes involvement and facilitates understanding of the interactive actions, plays a pivotal role in gesture-based interaction design.

6 DERIVE MEANINGS WITH METAPHORS

Following Lakoff and Johnson [83], we consider language as a proxy to study metaphor – imposing meaning in our lives – being a foundation of our behavior and conceptual system [141]. We break RQ3 down into two sub-questions: (1) what are the common metaphor TARGETs and SOURCEs? Also, (2) how to evaluate the meaningfulness of a given metaphor pair? To solve these questions, we first look for common metaphorical TARGET-SOURCE pairs from existing data sources. Second, we collect the human labeling on meaningful metaphors, which extend the objects with abstract meanings, train a model to predict metaphor meaningfulness, and rank metaphors according to the probability predicted. In this section, we report our data collection and model implementation procedures and analyze the computational results.

6.1 Meaning Derivation: Meaningful Metaphor Collection

We obtain an existing large metaphor dataset provided by Li *et al.* [89]. The dataset initially contains 922,234 unique metaphor pairs with pair-frequencies extracted from billions of web documents. All the metaphor pairs are identified based on a set of strict syntactic structures, excluding the hyponym and hypernym pairs (*e.g.,* APPLE is a FRUIT) [89]. Following previous practices, we consider simile structure as it instantiates a similar cognitive process – "describe one thing as though it were something else" [19] – which is similar to metaphor but uses a different language template [18, 83]. The dataset adopts the common simile structure "TARGET be/verb like [a/an] SOURCE", and metaphor structure "TARGET be [a/an] SOURCE" to identify the TARGET and SOURCE pairs. By matching potential SOURCE words with 721 unique objects given by the previous study, we get 29,002 metaphor pairs as a tentative dataset for further analysis. We conduct a pre-screening to remove any bad words from the tentative dataset, including profanities (offensive), swear words, curses, insults, and adult words. The bad word collection is a union of blacklisted words in the mainstream media (*i.e.,* Facebook, Google, and YouTube). After the pre-screening, the size of the metaphor pairs is reduced from 29,002 to 28,350.

We conduct another MTurk study to understand how people interpret the meaningfulness of a particular metaphor pair. Taking this opportunity, we filter out the low-quality metaphor pairs (*i.e.,* weak metaphoricity) from the dataset. We implement a web interface (Figure 7) for the second MTurk study and adopt the same recruitment criteria (*i.e.,* restricted to the USA, HIT approval rate $\geqslant 90\%$) from the previous study. To measure metaphor meaningfulness, we ask each worker to rate 50 TARGET-SOURCE pairs along the following "0-3" scale:

- 0 – Make no sense (Not meaningful/Not a metaphoric structure): the pair does not share any connections or similar features, or the pair may be a hyponym and hypernym but not a metaphor;
- 1 – Make weak sense (Low-meaningful metaphor): the pair may share a remote connection that needs further explanation;
- 2 – Make fair sense (Medium-meaningful metaphor): the pair may have a moderate connection with each other according to worker's experiences;
- 3 – Make strong sense (High-meaningful metaphor): the pair evoke an immediate and clear connection that is easily/readily comprehensible.

To maintain the quality of our collected data and make sure the workers have fully understood the rating scale, we provide instruction with example ratings at the beginning of the study and set validation checks by leveraging the known answers in our quality control policy. That is, we design four questions with different scores at random positions on the question list: two pairs with hyponymy/hypernymy/co-hyponym structures or not meaningful enough, and they should be

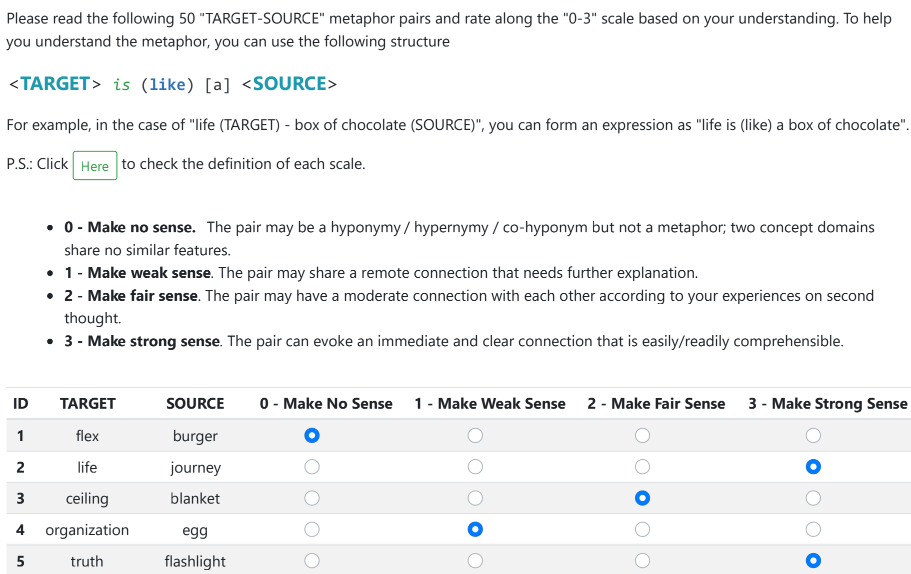

Figure 7. The user interface of the meaningful metaphor labeling MTurk study. The screenshot demonstrates the first five decisions made by one participant.

scored as “0”, *e.g.,* LEMON - FRUIT; two other pairs are widely used as metaphors, and they are not supposed to be scored as “0”, *e.g.,* LIFE - JOURNEY.

During the study, each metaphor pair is evaluated by five MTurk workers. Pairs are randomly sampled from the metaphor dataset and being continually fed into the MTurk study until the labeled pairs are large enough that model performance ceased to increase. We use the value of Area Under a Curve (AUC)[3] to indicate the model performance. To determine whether the number of the labeled pairs is enough, we apply a polynomial regression model ($degree = 3, R^2 = .71, p < .001$) to compute the trend of the AUC score. When the sample size equals 4,158.68, we find that the derivative of the polynomial regression model arrives at the value of zero, which means that the model's performance would unlikely be improved from this point. Therefore, we end the study with a collection of 4,260 valid metaphor pairs.

At the end of the study, 492 out of 532 unique workers are approved with their feedback (approval rate = 92.48%). The average task duration for each worker is 6.03 minutes, and those who provide valid feedback are rewarded with \$.50. A good degree of reliability is found in user ratings along the meaningful metaphor scale. The average measure intraclass correlation coefficient (ICC1k) among the five inconsistent raters is .68 with a 95% confidence interval from .66 to .69 ($F(4, 259, 17, 040) = 3.09, p < .001$). Following the method adopted in [106], we label metaphor pairs with a mean rating larger than two as a positive, meaningful metaphor according to our scale definitions. Otherwise, we label them as negative. Among 4,260 valid metaphor pairs, there are 3,846 negative pairs and 414 positive pairs in total.

6.2 Meaning Derivation: Feature Selection and Analysis

According to Parde *et al.* [106], we divide the features into two subsets, *i.e.,* psycholinguistic and conceptual. For the former features, we collect imageability and concreteness scores from the MRC Psycholinguistic Database [30] and concreteness ratings with a standard deviation from

[3]AUC stands for Area Under the Curve. The curve denotes the Receiver Operating Characteristics curve.

Table 3. Features extracted for identifying meaningful metaphor pairs (T: TARGET; S: SOURCE).

Feature	Total Number of Dimensions: Description	Top 20 Feature Importance	Source
Concreteness Rating Diff.	1: The difference of concreteness ratings between T & S	#1	Brysbaert[23]
Concreteness Rating	2: Concreteness ratings of T & S respectively	#2 on S	
Std. of Concreteness Rating	2: Std. of annotators ratings on T & S respectively	#4 on S	
Imageability Score Diff.	1: The difference of imageability scores between T & S	#5	MRC[30]
Concreteness Score Diff.	1: The difference of concreteness scores between T & S	#14	
Concreteness Score	2: Concreteness scores of T & S respectively	- (*#515* & *#611* respectively)	
Imageability Score	2: Imageability scores of T & S respectively	- (*#585* & *#612* respectively)	
Cosine Similarity	1: The cosine similarity between T & S embeddings	#3	Google[4]
Word Vector	300: 300-dimensional Word2Vec embedding of T	#6-10, 12, 13, 15-20 (13/300)	
	300: 300-dimensional Word2Vec embedding of S	#11 (1/300)	

the Brysbaert Concreteness Ratings [23]. These two scores help detect general metaphors [*e.g.*, 105, 137]. For the remaining features, we adopt Google's pre-trained Google News embeddings[4] and employ Gensim[5] to load the embeddings. There are a total of 612 dimensions included in the final feature space. Table 3 lists all the features adopted in our model and their descriptions.

To identify which feature is dominant in telling whether a metaphor pair is meaningful, we calculate the feature importance from the model. Such feature importance is generated based on the maximum information gain of the decision tree split during the boosting [71]. The ranking of feature importance is also presented in Table 3. According to the results calculated from our collected data, the top-rated individual feature set is the concreteness rating difference between TARGET and SOURCE. The Brysbaert's concreteness ratings [23] for English words contribute effectively in identifying meaningful metaphor pairs as the features generated from that dataset occupy three of the top five positions. Such a result is also related to the sample words contained in each dataset (*e.g.*, the Brysbaert's presented for 37,058 English words). The features of the SOURCE's concreteness ratings outperform the TARGET's partly because the source domain in a metaphor pair is typically concrete [34].

6.3 Meaning Derivation: Prediction on Metaphor Meaningfulness

We implement the probability prediction model using LightGBM[6], which is a gradient boosting framework. LightGBM can achieve almost the same accuracy while speeding up over 20 times faster than a conventional Gradient Boosting Decision Tree, which is currently state-of-the-art in many machine learning tasks [72]. To tune model parameters, we perform 5-fold cross-validation on the labeled meaningful metaphor dataset. The tuning is done by grid search and evaluated by the average AUC of validation sets with the final parameters of $max\_depth = 5, learning\_rate = .01, min\_data\_in\_leaf = 8$. To avoid overfitting, we limit the number of trees (*num_boost_round*) to 4,074, which is the index of the best tree in our parameter tuning. With these optimal parameters, we take the entire labeled dataset as the training set and retrain the model to predict the probability of meaningfulness for all metaphor pairs. Therefore, the meaningfulness of two metaphor pairs can be compared, such that rankings can be made. To make Metaphoraction efficiently present design idea candidates, we rank metaphor pairs according to their meaningfulness: the higher the probability of meaningfulness, the more worthy the pair appears in the front (see Section 7.1). Finally, we join the data collected from the gesture annotation study and the metaphor pairs on the "object" and "SOURCE" columns. The final dataset contains 5,383 unique records of TARGETs

[4]https://code.google.com/archive/p/word2vec/, this tool implements the computation of words with vector representations.
[5]https://radimrehurek.com/gensim/, an open-source library for unsupervised natural language processing.
[6]https://lightgbm.readthedocs.io/en/latest/, a gradient boosting framework that uses tree based learning algorithms.

(*a.k.a., meaning* in Metaphoraction), whose SOURCEs are objects collected from the previous study, with predicted probabilities of meaningfulness.

7 INTERFACE DESIGN AND IMPLEMENTATION

We implement Metaphoraction in a web application for further evaluation. This section describes the interface design process and the implementation details, including the dataset adopted for the web application from previous studies.

7.1 Interface Design

To support the generative ideation process, we follow the Visual Information-Seeking Mantra [127] to design the visualization and interaction of Metaphoraction. This creativity support tool aims to fulfill the following tasks (T):

- (T1) Support searching for random keywords in any components;
- (T2) Demonstrate the relationship between different components based on query results;
- (T3) Enable multi-directional and multifaceted exploration of all the components; and
- (T4) Track browsing history for user reference.

Based on these tasks, we design a medium-fidelity prototype and conduct a preliminary usability test with 26 university students with design backgrounds (12 female, $age_{Mean} = 21.77, age_{SD} = .64$). This study aims to identify whether our interface design for Metaphoraction could support the claimed tasks and basic ideation workflow. We recruit volunteers through advertising in an HCI course from a local university, and those volunteers receive one grade point as a token of appreciation after completing the task. During the test, we first explain to all the participants how to use Metaphoraction. Then we ask them to propose an interactive design idea for promoting sustainability campaigns on campus with the help of the Metaphoraction prototype. After the study, we collect the participants' feedback through semi-structured interviews. Their feedback indicates that our interface design is "*refreshing and simple to use*" (P3, male, 22) and "*helpful for understanding the relationships between the four components*" (P15, male, 22). Participants feel "*free*" (P11, female, 23) when they use the tool for interactive design creation and it is "*useful for idea generation*" (P16, male, 22). They also suggest improving the navigation functions to narrow down the searching scope of the design idea candidates and enabling undo functions to revoke current operations. We iterate the interface design process based on the collected feedback.

7.2 Implementation

7.2.1 Resulting Dataset Description. After joining the data collected through previous studies, we generate a final dataset with 588,770 unique records of gesture-based interaction design idea candidates with metaphorical meanings. The dataset consists of four components (*i.e., gesture*, *action*, *object*, and *meaning*), the metadata, and the meaningfulness probability results. The number of unique items in each component is 52, 485, 721, and 5,383, respectively. All the keywords are frequently used vocabulary words in English. For each design idea candidate, the metadata includes (1) demonstration animated GIFs, (2) interactive gesture source information, (3) available sensors or algorithms and supported devices for each *gesture*, and (4) a set of synonyms and explanations retrieved from *WordNet* [91] for each *action*, *object*, and *meaning* component.

7.2.2 User Interface. We present the final user interface of Metaphoraction as shown in Figure 8. By typing any keyword(s) of a potential design idea in the search box (Figure 8 ❶, T1), Metaphoraction retrieves the corresponding design idea candidates by an exact-match lookup function. Then it demonstrates the overall relationships among the four components (Figure 8 ❷, T2) and the total number of returned results (Figure 8 ❸, T3) to users. Metaphoraction adopts a Sankey

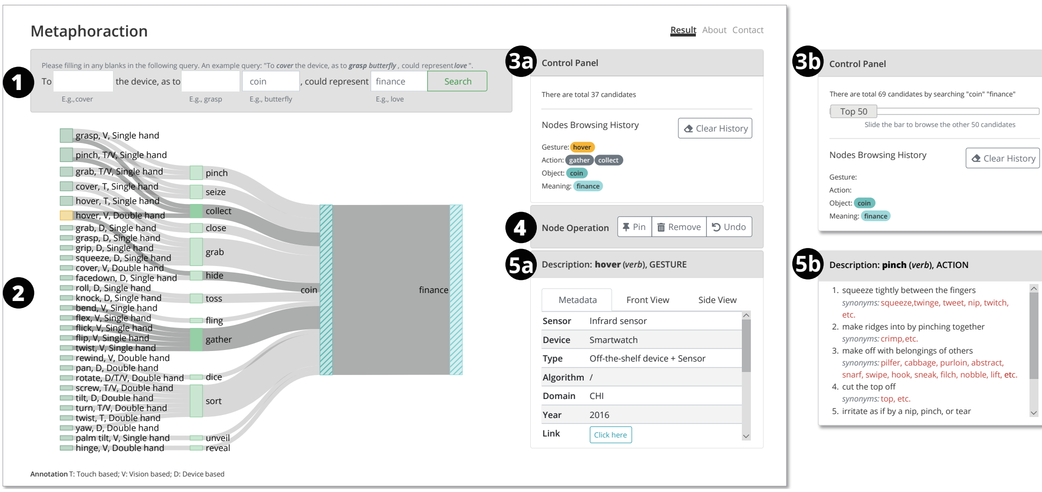

Figure 8. The interface of Metaphoraction. The screenshot was captured from E2's search results (see Section 8.3) with input "*object*: coin" and "*meaning*: finance" during the design workshop. ❶ is the search box; ❷ is the Sankey diagram visualizing the possible design idea candidates; ❸ is the control panel; ❹ is the node operation panel; ❺ is the description view.

diagram visualization to depict the flow from *action* to *meaning* since it needs to reveal a many-to-many mapping between multiple domains. Each node represents one item in the corresponding component, and each link represents the connection between any two items. Due to the limited visualization space, Metaphoraction presents 50 candidates on each screen, and users can scroll a sliding bar in the control panel to browse the remaining candidates (Figure 8 3b, T3). We rank the design idea candidates by the meaningfulness probability of the involved metaphor pairs. To help designers find ideal design ideas with specific components, we provide functions to allow users to filter candidates by pinning the target node(s) or removing the undesired node(s) (Figure 8 ❹, T3). We track users' browsing history and highlight those details for their reference (Figure 8 ❷ and ❸, T4). Users can also withdraw the current search and go back to a previous action (Figure 8 ❹, T4). Metaphoraction also provides metadata to each node for users to interpret the suggested candidate (T3). To be more specific, for the *gesture* nodes, we list detailed information such as gesture demonstration from both the front and side views, related sensors and devices, supported algorithms, and meta-information of the related research (Figure 8 5a, T3); for the *action*, *object* and *meaning* nodes, Metaphoraction suggests synonyms help users divulge their thoughts and expand their horizons (Figure 8 5b, T3). We also provide definitions for the selected nodes in case the given words in the suggested candidate are limited by the given context (Figure 8 5b, T3).

7.2.3 Technical Details. We use the *Flask* server to host the web application and deploy the *SQLite* database to enable a search with the user-submitted query. We adopt *WordNet* synsets in the *NLTK* package to find related synonyms and explanations for each word.

8 EVALUATION ON METAPHORACTION

We conduct a design workshop with a design team, including two interaction designers: E1 (female, 30), E2 (female, 28); two user experience designers: E3 (female, 28), E4 (female, 29); and one design executive: E5 (male, 33), from a local company. This team is responsible for designing user interfaces and preparing graphical materials across multiple devices. Our goal is to explore how design experts use Metaphoraction in various advertisement design tasks during the ideation process. We aim to answer the following questions: (1) Does Metaphoraction help to improve creativity and productivity of interaction design ideation? (2) How would designers use the tool to assist their ideation for different tasks? Furthermore, (3) how would designers select and interpret the potential candidates?

8.1 Design Workshop Procedure

We hold a design workshop with a professional design team, of which all members have over five years of experience designing interactions for mobile applications or interactive media. At the beginning of the workshop, we present an overview of Metaphoraction's background to ensure that all experts have the same level of knowledge in using this creativity support tool. The presentation (~10 minutes) includes (1) the goals that Metaphoraction intends to achieve, (2) the components that Metaphoraction consist of, as well as (3) the principles and processes on how we built the tool. Then we introduce Metaphoraction to all experts, walking them through each user interface component, visual encoding, and interactions. We also invite those experts to explore the tool freely and raise questions about Metaphoraction (~10 minutes). Next, we ask the design experts to complete four design tasks separately (~50 minutes overall, details in Section 8.2). At the end of the workshop, we invite attendees to share their experience and provide feedback (including advantages, limitations, and possible future use) with in-depth interviews (~20 minutes). Findings of the interview are reported in Section 9.

8.2 Design Tasks

Following the Generic Creative Process model [146] and common searching behaviors [22, 57], we ask each expert to generate design ideas based on the following four design scenarios:

(1) *Designing for a specific topic*: to discover as many design idea candidates as possible for an interactive promotion advertisement of a particular financial product developed by the company;
(2) *Designing for a specific topic in a particular context of use*: to find the optimal design idea candidate for a mobile interactive promotion advertisement of a particular financial product posted on a mainstream e-commerce website;
(3) *Transforming an existing design*: to convert a popular short video advertisement created by the company to interactive digital content; and
(4) *Validating an existing design*: to verify the design rationale behind a previous interactive advertisement campaign launched by the company.

For tasks (1)–(3), we ask the experts to present their ideas as design sketches.

8.3 Results of Metaphoraction Usage

All five experts express enthusiasm for using Metaphoraction in generative ideation. Overall, they report that Metaphoraction improves the creativity of design ideas compared to past experiences by counting the number of ideas generated. Their unique experience includes gaining inspiring options for novel interaction design and potential meanings extended beyond the initial input. Moreover, experts feel that their productivity benefits from detailed descriptions, which supports verifying technical feasibility, "fosters sense-making by referring to word explanations and related synonyms" (E2), and "provides connected instances" (E1) within each design component. We summarize how experts perform the four design tasks when using Metaphoraction in the subsequent paragraphs of this section.

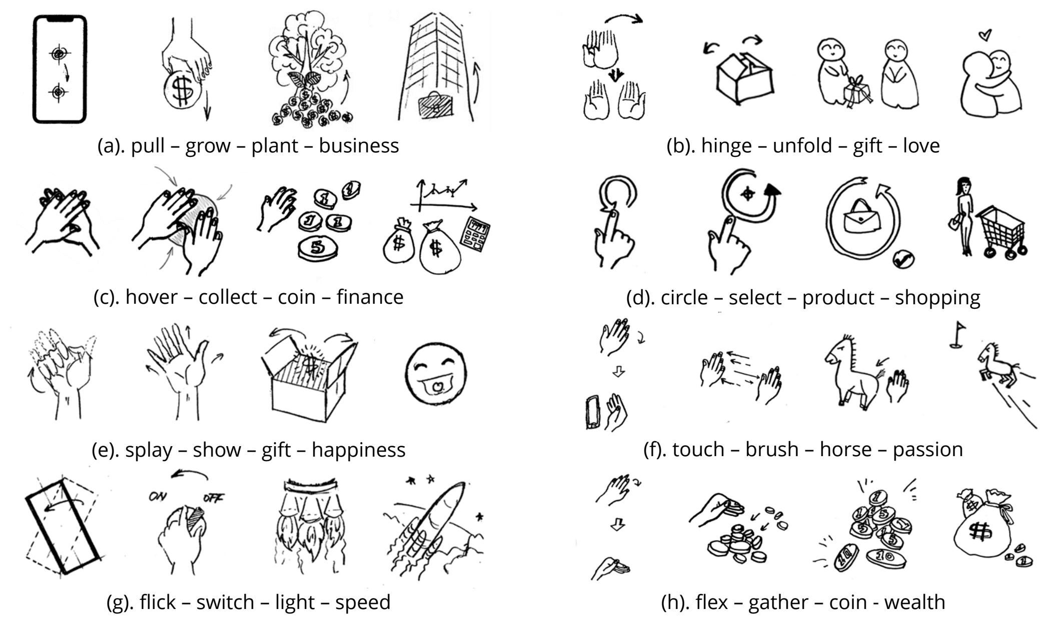

Figure 9. The sketches are designed based on Metaphoraction's design idea candidates during the workshop.

In Task 1, the design team was asked to create all possible design ideas for a loan product designed for enterprises and corporations. All experts tended to start by searching keywords of figurative meanings according to the given theme. The most frequently chosen keywords across all experts were "finance", "debt", and "organization"; E1 also tried "business" and "solution", E2 added "service", and E5 included "money" and "cooperation" as extra queries. After retrieving the results, designers further updated their original ideas by referring to the other possible design solutions. For instance, E1, E3, and E5 proceeded to explore more concrete objects, like "gift" and "purse", to look for more exciting results. "*The tool creates a lens that allows me to see my thoughts in different ways...I came up with ideas which I could have hardly imagined*", as E1 raved about the creativity of Metaphoraction. Although the input queries each expert brought to the tool were quite different, Metaphoraction was able to return diverse and distinct outcomes instantly, which demonstrated its productivity. At the end of Task 1, which lasted no more than ten minutes, we collected a total of 23 unique design ideas that experts thought interesting to implement. Examples of selected candidates included but were not limited to "pull - grow - plant - business" (Figure 9.a), "hinge - unfold - gift - love" (Figure 9.b), and "hover - collect - coin - finance" (Figure 9.c).

In Task 2, the design experts each needed to specify one idea that was the most suitable for mobile advertising on an e-commerce website, and they could use candidates generated in Task 1. E2 and E4 started their ideation with topic-related keywords "promotion", "shopping", "discount" or "sales", while E5 set forth to query more abstract meanings like "happiness" and "freedom". In contrast, E1 and E3 chose to change the objects in their previous design solutions from "purse" to "product" and "coin", and tried with the entries starting from everyday mobile interactions, *i.e.*, "tap" and "splay". E3 explained that Metaphoraction provided an opportunity to build upon previous design ideas, "*when I encountered new constraints, I used to restart the whole design process...(sometimes) starting from nothing...but here I am able to reuse my previous design, which sometimes has great value, and just replace any inappropriate parts and take a new direction*". When more design constraints were

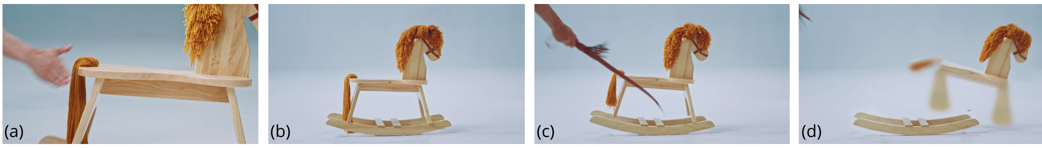

Figure 10. The screenshots of video adopted in the third task of the design workshop. The video is captured into four main scenes: (a) a hand is trying to push a wooden horse; (b) the wooden horse keeps stable; (c) a horsewhip, which represents a loan, is waved towards the wooden horse; (d) the wooden horse gallops off.

added to the original design space, designers reported that they used to spend too much time trying to adjust the idea search scope, and Metaphoraction improved their productivity. With the help of the ideation support, the creativity enhancement brought about by Metaphoraction also enlightened designers with possible alternative design choices during the idea iteration process. The selected design ideas, which were suitable to implement into the mobile device and fit into the promotion theme, included “circle - select - product - shopping” (Figure 9.d), “splay - show - gift - happiness” (Figure 9.e).

In Task 3, we first played a 12-second video advertisement posted by the company before. The video showed a hand trying to push a wooden horse in the main scene, but the wooden horse would not move until a loan is applied as an incentive (Figure 10). According to this advertisement, all participants first tried to find ideal gestures based on the character. E2 and E3 started by searching “horse” as the *object*. E4 put a spin on it and queried the meaning “speed”. Instead of looking for possible gestures, E1 and E5 further changed their strategy for this task: they started with the existing gesture ideas (*e.g.,* “tap”, “slash”) and aimed to find alternative objects to replace the “horse” presented in the video. “*I can obtain useful feedback when I submit my queries in the search box...It (Metaphoraction) inspires me on formulating new ideas from different aspects, like the gesture, the objects that could be used, or the meaning that I could express...*”, commented by E1. These comments show that Metaphoraction allows designers to make their queries from different directions based on the original design creatively. Such flexibility supports both a material-driven design process (the materials designers have obtained) and a goal-driven design process (the core idea that designers want to express). This also proves that Metaphoraction provides alternative design idea candidates productively. Some inspiring ideas generated in this task are “touch - brush - horse - passion” (Figure 9.f), “flick - switch - light - speed” (Figure 9.g), and “flex - gather - coin - wealth” (Figure 9.h).

In Task 4, both E1 and E5 commented that Metaphoraction could provide back-ups of their creative design ideas. As E1 reflected, “*previously, we implemented a single tap to interact with the digital content in case a newly designed interaction is too novel for the general audience...the tool (Metaphoraction) shows rotating the phone as an applicable interaction, just as one of our proposals. It provides evidence for our design and also guides us with feasible technical solutions*”. E5 appreciated Metaphoraction for its ability to support productivity, “*this tool helps me drill down to more specific design details for each design component efficiently...I used to test different ideas iteratively multiple times with my colleagues and friends*”. During the whole study, participants leveraged the synonym features to look for alternatives, as E1 mentioned “*I refer to those synonyms to update my keywords...every time I can find some new ideas after checking them*”.

During the workshop, we also received feedback on potential issues and suggestions to improve Metaphoraction. According to those design experts, the main drawback of the current version is that the scope of the provided instances is limited. E2 pointed out one issue at the beginning when using Metaphoraction, “*I do not find the meaning that I want to present...*”. However, “*...I am able* *to transfer my initial idea into another design with the help of synonyms, and I find similar ideas based on the given (design idea candidates)...*", as E2 commented after completing all the tasks with Metaphoraction. We further discuss this limitation in Section 10. Moreover, E5 suggested providing design materials or examples of different components in this tool. Such an improvement could potentially enhance Metaphoraction as an auto-generated interaction design prototype. As this suggestion is beyond the scope of this research, we discuss it as future work in Section 10.

8.4 Usage Patterns of the Creativity Support Tool for Interaction Design Ideation

Overall, we cover four distinct design scenarios through the workshop to illustrate standard design practices when using creative support tools for interaction design ideation. We identify three main usage patterns:

(1) *Exploration.* Users only have limited keywords and are not clear about the overall interaction design pipeline. They may try the creativity support tool with several searches and build up whole interactive design ideas with suggested terms.
(2) *Seeking optimal solution(s).* Users have partially well-defined or fixed options for certain components. They want to use the creativity support tool to help them fill in the missing parts with a practical guide.
(3) *Validation.* Those users already have some initial ideas about the design pipeline, but they may not be confident about the proposals. They want to examine their design ideas by looking for backups or alternative solutions.

The identified usage patterns can benefit the future design of support tools with specific usage directions.

9 DISCUSSION

In this section, we further discuss our findings on designing interactions with Metaphoraction. We first reflect on the commonalities in the design of gesture-based interactions with meaningful user experience. Next, we reveal the generality of Metaphoraction and propose potential application domains that could benefit from our tool. Regarding the above two issues, we derive several considerations for the future design of gesture-based interactions with meanings.

9.1 Towards Meaningful Gesture-based Interaction Design

Previous works [25, 36, 54, 99, 123] stressed the increasing need for and interest in designing meaningful user experiences in both HCI research and technical practices. It is recommended that a design should first be functional and reliable to complete the task, then become accessible and convenient to simplify the interactive procedure, and eventually create more pleasurable experiences [6]. Feedback from in-depth interviews with the professional design team confirms these three stages in gesture-based interaction design and further sheds light on the design for meaningful experiences.

Ensure basic functionality. According to the design team, the gestural interactions should first fulfill a need, be "*easy to conduct and intuitive*" (E1-5), and "*should not sacrifice the efficiency*" (E1, 4, 5) when performed to accomplish the required tasks. At this first stage of gesture-based interaction design, designers should primarily focus on creating or reusing a gesture to deliver practical benefits. Building on existing mobile and wearable gestures, Metaphoraction ensures the gestural candidates provided have been verified and evaluated in previous research. The design team felt that the metadata about each gesture of interest (Figure 8 5a, *e.g., device*, *sensor*, and the *link* to the source file) provided in Metaphoraction was useful in helping them to determine its practicality in a target usage scenario. The tool can save time and effort searching for potentially usable gestures and provide a sound justification for the ease of execution and promotion of their design.

Enhance accessibility. The interaction should conform to basic common sense and consider the abilities and social roles of the target users. As suggested by our interviewees, "*...the design process is usually iterative and should involve users with diverse knowledge backgrounds and motor skills*" (E5). In other words, designers should put themselves in the users' shoes, be empathetic, and pay attention to the details at every interaction step and the context in which the gestures are intended to be performed. Our interviewees found that the number of gestural interactions mapped to a candidate action shown in the Sankey diagram (Figure 8 ❷) could reflect the flexibility of the corresponding design idea to be implemented in different settings. Furthermore, the associated objects distinguish the manifestations of the listed actions, and the potential meanings set the scope of expressible concepts.

Assign meaning and value. According to the User Experience Hierarchy of Needs Model [6, p. 12] that demonstrates the relationships among all the needs required for user experience design, practitioners consider "meaningfulness" as the ultimate level of a design. The design team particularly appreciated the use of Metaphoraction for this purpose, as it could help expand the scope of the concepts that the gestures could represent by leveraging metaphors. The designers further noted that the interactions should be informative and comprehensible to users. They considered the action description in Figure 8 5b and the popularity ranking in Figure 8 3b of Metaphoraction helpful to inspect the possible interpretability of a candidate gesture. Last but not least, those experts mentioned that playfulness – which may accompany novelty and the embodied experience of a design – is a by-product and extra value of having a meaningful experience during the interaction. As E5 commented, "*I can design a delightful experience with the first three components (i.e., gesture, action, and object)*". E2 also replied, "*To hover the phone to 'collect coins'...it (the idea) sounds unique and playful to me*".

9.2 Potential Application Domains of Metaphoraction

Representing metaphorical meanings through gesture-based interactions has a great potential for enhancing user experience with the advances and richness of sensory technologies. In this paper, we demonstrate the use of Metaphoraction for advertisement design, but this does not limit its application in supporting various other ideation tasks for different purposes. Designers can customize the input and filter the search results according to their specific goals. Our invited design experts envision several promising application domains in which such enhancement can take place.

Educational material design. As it is easy to access mobile and wearable devices nowadays, educational applications have a great potential to provide learning materials with abstract meanings or concrete objects through gesture-based interactions. "*...Incorporating gestures into the learning process allows users to use an embodied experience to develop memory*" (E4). Previous work [8, 16] has also proved that learning may benefit from embodiment and metaphors, especially for children who learn by exploration and gain experiences through interactions. Antle *et al.* [8] adopted the "interactional metaphor" that involves embodied schemata to help children "understand one thing in terms of another". *Moving Sounds Tangibles* [16] tried to identify suitable metaphors through embodied schemata based on abstract concepts. To understand a metaphorical meaning toward interactions sometimes requires effort but gives something in return. This is because metaphors can be an opportunity to create a sense of familiarity and a cue to reason about and understand the world [83].

Game design. Gesture-based interactions with metaphorical meanings promote the conceptualization of abstract phenomena and introduce novel, playful, and realistic interactive experiences to enrich the overall user experience. E5 mentioned that the gaming industry is in great demand for meaningful gesture-based interaction designs, arousing curiosity, creativity, spontaneity, and amusement during gameplay. For example, an award-winning web-based game, Five Minutes [12], adopts skeuomorphic drag and hold interactions, allowing the experience to be playful and exploratory, and leaving the users with no doubt about how they should interact in the gaming context.

Marketing, promotion, and advertising design. As audiences are used to "*allocat(ing) limited time to advertisements*" (E4), the ultimate goal of marketing and advertising design is "*to deliver thought-provoking content and interactions to attract, entertain, and impress potential customers*" (E5). Meaningful gesture-based interactions can potentially achieve a good balance between effectiveness and efficiency of information conveyance when incorporated into a product or service campaign. This is because metaphors can be a source of emotion, a trigger of motivation, or the cause of resonance [83].

9.3 Considerations for Interaction Design with Meanings

The design team shared their opinions on issues to consider when designing gesture-based interactions with meaning. We summarize their feedback in three key points.

Target user groups. On the one hand, designers should ensure that target users could efficiently perform the interaction. Primarily, it is crucial to consider whether intended users could complete the required gestures. For example, elders sometimes find it hard to perform high-frequency gestures within a short duration [31] while young children may have problems controlling fine actions due to their lack of dexterity [84, p. 98]. On the other hand, designers should consider cultural and social factors and ensure that the underlying meanings extended from the gestures should be well-recognized by the target audiences [62]. Interactions selected for particular groups need to be tested before applications.

Platforms. Accurate and reliable interaction recognition is crucial to the success of meaningful gesture-based interactions. The recognition requires precise data captured from device sensors. Therefore, an interaction design space is restricted by the availability of necessary sensors on the intended interactive devices and scenarios. When designing for social media or web applications, designers should ensure that the data can be safely captured from the majority of devices but not limited to specific models. Also, if the interactive design needs to be embedded in existing media services, designers need to check whether the service provider supports the sensing of required user interactions for third parties. When designing a promotion spot or stand-alone machine, designers may consider extending the interaction space by adding extra sensors on interactive devices to attract the target audiences.

Novelty and practicality. Well-established guidelines indicate that interaction designs should consider users' best practices [56]. This rule also applies to meaningful gesture-based interaction design. "*I once got complaints about newly designed interactions...users thought they just needed to click the image as usual, but surprisingly, they needed to brush the whole content*" (E1). To avoid making interactions cumbersome or obstructive, designers need to figure out the following three questions before implementing their design ideas into practice: (1) What is the goal for making the gesture-based interactions meaningful? (2) What would be gained/lost by using meaningful design in existing applications? (3) Do the gains outweigh the losses?

10 LIMITATIONS AND FUTURE WORK

This work has several limitations. First, we only focus on the upper-body interactions supported by mobile and wearable sensors due to our research scope. We believe our tool can easily be extended by including more complicated interactions supported by other devices or media, *e.g.*, tabletops, screen walls, and augmented/virtual reality. Second, this work is not intended to be philosophical and thus does not intersect with fascinating and densely layered issues about the nature of metaphor. Taking cross-cultural variation in metaphor as an example, we only involve workers from the USA in our crowdsourcing experiments, and we are aware that individuals from different backgrounds and cultures may interpret interactive gestures and metaphors differently. When dealing with specific metaphors, we recommend being cautious about their socially shared backgrounds [156]. Therefore, one of our future works is to know how cultural background would affect Metaphoraction's output. Third, we do not conduct controlled studies to see how Metaphoraction improves the quality of ideation results due to the lack of a fair comparison that provides similar support. Our qualitative evaluation with design experts only provides us an in-depth understanding of how designers would use Metaphoraction and proves the value of the ideation pipeline with metaphorical meanings.

In the future, we may look into the use of Metaphoraction from a quantitative perspective by referring to the ideation outcomes. Moreover, we consider expanding the scope of the gesture annotation and meaningful metaphor pair collection and gaining more insights (*e.g.,* providing the ground of TARGET-SOURCE pairs to inform the tactics that could simulate creative thinking) into meaningful interaction designs. This is because the meanings proposed by the crowd workers may sometimes not readily be translated into usable ideas without a design interpretation. We can extend the interaction design space into an ambient display and augmented/virtual reality setting (*e.g.,* the example of *Social Swipe* and *TetraBIN* in Figure 1.d and Figure 1.e) and collect more possible interactions designed with the updated sensor technology. We also see the potential of auto-generating interactive content by augmenting the creativity support tool with related design materials. Metaphoraction will create meaningful interaction design demos with pre-specified or interactively defined parameters, for example, the size and format of the design material, the interaction scale, and so on. Such a tool can be further customized to the needs of individual companies or design teams to reduce designers' workloads.

11 CONCLUSION

This paper presents Metaphoraction, a creativity support tool for gesture-based interaction design with metaphorical meanings. This tool supports designers in systematically exploring the metaphorical meaning of gesture-based interactions; in other words, it provides a web interface to facilitate the exploration of design idea candidates, consisting of four distinct components, *i.e., gesture*, *action*, *object*, and *meaning*. We connect these four components through three steps. First, we conduct a literature survey of 71 papers on commonly adopted upper-body mobile/wearable interactive gestures. Second, we invite crowd workers to translate those interactive gestures into daily actions plus associated objects based on their similar appearances, movements, and experiences when performing those actions. Third, we explore the potential extended meanings of those objects through metaphorical mappings with probabilities predicted based on crowdsourced ratings. Experts from our design workshop suggest that Metaphoraction can support the ideation of meaningful gesture-based interactions with improved productivity and creativity. We discuss how our insights evolved into a meaningful interaction design and present future work which could further empower interaction designers.

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