GestuRING: A Web-based Tool for Designing Gesture Input with Rings, Ring-Like, and Ring-Ready Devices

Radu-Daniel Vatavu
MintViz Lab, MANSiD Research Center
Ştefan cel Mare University of Suceava
Suceava, Romania
radu.vatavu@usm.ro

Laura-Bianca Bilius
MintViz Lab, MANSiD Research Center
Ştefan cel Mare University of Suceava
Suceava, Romania
laura.bilius@usm.ro

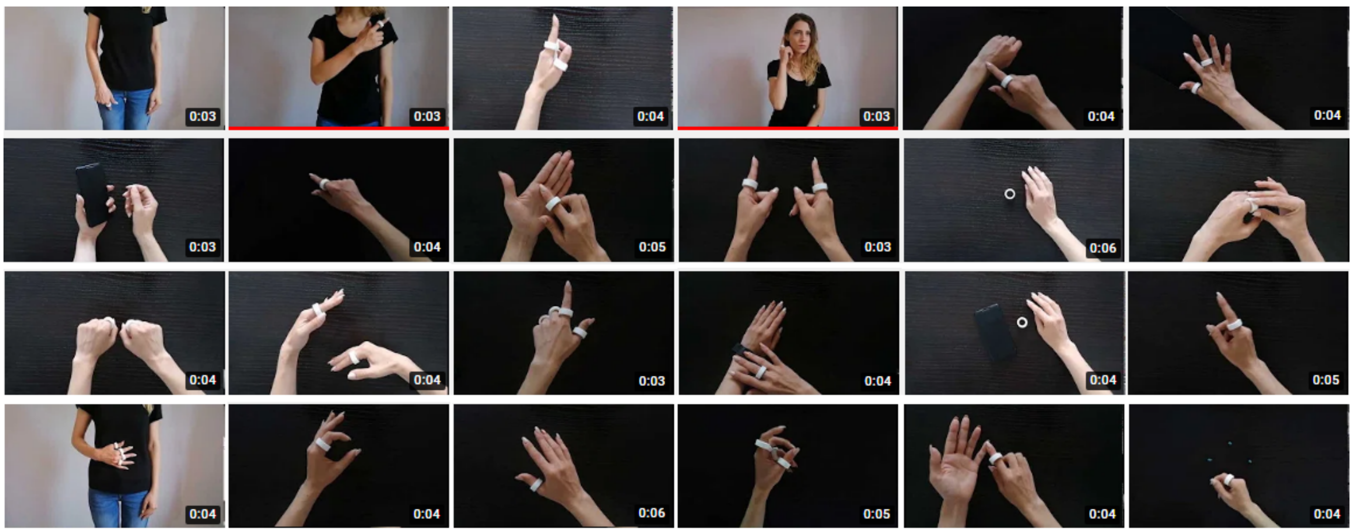

Figure 1: Ring devices enable a variety of gesture-based interactions, from touch to mid-air to on-body input. Our web tool, GestuRING, features a database of 579 mappings between ring gestures and system functions, e.g., rotate the ring on the finger to navigate a 1D menu, together with a YouTube video library to illustrate the gestures, as shown in this figure.

ABSTRACT

Despite an exciting area with many promises for innovations in wearable interactive systems, research on interaction techniques for smart rings lacks structured knowledge and readily-available resources for designers to systematically attain such innovations. In this work, we conduct a systematic literature review of ring-based gesture input, from which we extract key results and a large set of gesture commands for *ring*, *ring-like*, and *ring-ready* devices. We use these findings to deliver GestuRING, our web-based tool to support design of ring-based gesture input. GestuRING features a searchable gesture-to-function dictionary of 579 records with downloadable numerical data files and an associated YouTube video library. These resources are meant to assist the community in attaining further innovations in ring-based gesture input for interactive systems.

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CCS CONCEPTS

• **Human-centered computing** → **Gestural input**.

KEYWORDS

Smart rings, gesture input, web tool, review, video library.

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1 INTRODUCTION

Gesture input for interactive systems, from personal mobile devices and gadgets [21,96,126] to smart home appliances [25,89,124,128] and large displays [41,58,105], presents many benefits to users, among which naturalness [60,110], intuitiveness [75,81,116], learnability and memorability [26,78], articulation efficiency [17,62], expressiveness [2,14,88,114], and subtlety [4,27,92] have been regularly advocated in the scientific literature. Among gesture input devices, smart rings hold a privileged position due to the wide heterogeneity of gesture types they can sense, from touch and multitouch [11,12,66] to free-hand [112–114], mid-air [126,130,133,134], on-body [77,85,102], and grasping gestures [118,120]. This versatility, next to their small weight and tiny form factors, makes ring devices suitable for a variety of interactions and contexts of use, e.g., rotating the ring across the finger to navigate a 1D menu [4], tapping in mid-air with the finger wearing the ring to confirm selection [42], swiping the area of a room with the pointed finger to reveal home appliances to control [59], input on the skin for application shortcuts [131], thumb-tip tapping on the index finger for eyes-free text entry [122], or thumb-to-index swipe gestures to browse music [34]; see Figure 1 for illustrations of such gestures from our YouTube video library. Also, prior research has shown how the vantage point of the ring as a sensing device can be leveraged to enable bimanual [33], spatial [9], subtle [4], always-available [124], and context-aware [15] input towards the realization of ubiquitous computing environments [94,95]. These desirable characteristics spotlight smart rings as distinctive input devices in the landscape of mobile and wearable gesture sensors and gadgets.

However, research on ring-based gesture input is scattered in the scientific literature in a landscape that mixes contributions from wearable computing, human motion sensing, gesture recognition, interaction devices and techniques, and engineering interactive systems. *The researcher or practitioner interested in a representative photograph of this landscape experiences the tension between an exciting area with many promises for innovation and the lack of structured design knowledge and readily-available resources on which to build in order to attain those innovations.* This state of things makes it difficult for (i) newcomers to readily overview what has been achieved in ring gesture input, (ii) experienced researchers and practitioners to easily access, validate, and consolidate knowledge, and (iii) system designers from connected areas, e.g., e-Health [12, 87], assistive technologies [11,30,79], automotive UIs [10,32], etc., to readily locate key results for applications that use rings. Our goal is to structure this fragmented landscape and to provide resources to foster design and engineering of interactive systems employing ring gestures. To this end, our practical contributions are as follows:

(1) We conduct a systematic literature review (SLR) and report results from a meta-analysis of 84 papers addressing ring gesture input. Our results complement Shilkrot *et al.*'s [98] generic survey of finger-augmentation devices (FADs) and Rissanen *et al.*'s [92] overview of ring-based user interfaces (UIs) by addressing a distinct scope of investigation and new research questions. To structure the diversity of the ring prototypes from the literature, we introduce new terminology to distinguish among *rings*, *ring-like*, and *ring-ready* devices.
(2) We complement our meta-analysis of the literature on ring-based input with a qualitative analysis of 954 ring gestures extracted from the papers we surveyed, which we use to compile a dictionary of 579 mappings between ring gestures and system functions, e.g., rotate the ring across the finger to navigate a 1D menu [4]. To render our results actionable for researchers and practitioners, we release this dictionary in the form of a web-based tool, GestuRING, with downloadable gesture numerical representations and a companion YouTube video library demonstrating the gestures. We discuss use cases to illustrate how GestuRING informs and supports design of gesture UIs for ring-based interaction.

2 RING GESTURES, RINGS, RING-LIKE, AND RING-READY DEVICES

We start our discussion with an operational definition of "ring devices," as part of the general class of FADs [98], and of "ring gestures," respectively, to specify precisely our scope of investigation.

Following Gheran *et al.* [31], we understand by ring gestures *"any action performed with or on a smart ring or any movement of the wearing finger and/or hand that causes a detectable change in the ring's position and/or orientation in a system of reference centered on the user's finger or body"* (p. 625). This generic definition is useful for our scope as it encompasses a variety of possible gesture-based interactions, from touching and manipulating the ring [23] to movements of the wearing finger and/or hand [31], including bimanual actions where rings are worn on both hands [33].

In the above definition, rings are unspecified finger-worn devices that enable gesture-based input of various kinds. However, not all finger-worn devices are rings: FADs also include distal addenda, whole-finger devices, fingernail addenda, finger sleeves, devices designed for the thumb, gloves and devices for the palm; see Shilkrot *et al.* [98] for a survey. From this perspective, a simple definition of a ring device is a FAD with the form factor of a ring. However, this definition excludes a large variety of prototypes that we found in the scientific literature referred to by their authors as "rings" and that enable ring gestures of the kinds specified above. Thus, to accommodate this variety of ring FADs, we introduce new terminology that characterizes such devices beyond their form factors.[1] Specifically, we identify two new categories of ring devices that we call *ring-like* and *ring-ready*. Ring-like devices are not restricted by the ring form factor, i.e., they instrument other parts of the finger, but enable the same kind of gesture input as rings. Ring-ready devices can be worn as rings, but also on other body parts and/or used in other ways than a ring. They are multi-form, multi-purpose devices that, among their multiple possible forms and uses, can also take the form of a ring and be worn and used as such.

These three categories of ring devices—rings, ring-like, and ring-ready—emerged from our analysis of the scientific literature on ring-based gesture input (details in Sections 3 and 4), but we prefer to introduce them right from the start to provide better context for ring gestures as well as to precisely specify our scope. These three categories contour *a family of ring devices* with characteristics that make them distinctively identifiable in the large spectrum of FADs [98]. Details and examples follow in Subsection 4.2.3.

3 METHOD

Our method for the investigation of ring gestures and devices consists of three Research Questions (RQs) and corresponding steps to answer those questions. The answers are important to (i) practitioners that wish to incorporate gesture input in their ring UI prototypes and need access to design and engineering knowledge, but also to (ii) researchers looking for an overview of this area:

[1] In our taxonomy, the size of the ring or whether processing is handled on another device to which the ring is connected (e.g., a micro-controller on a PCB affixed to the wrist or a laptop to which the ring device sends data by wires) are not relevant since they reflect aspects that can be fixed with professional product design and miniaturization. Thus, we consider finger-worn devices to have a ring form factor even if the ring is bulky [8,11,34,43,80,90] or connected with wires to another device that handles gesture processing [13,38,40,51,57,67].

RQ_1: What are the most popular sensing and recognition techniques that have been employed in the scientific community to detect and recognize ring gestures? Relevant subquestions regard sensing technology (e.g., imagining [101, 103], inertial [65,121], magnetic [4,21], etc.) and recognition algorithms (e.g., DTW [119,123] or SVMs [93,132]).

RQ_2: What types of gestures have been proposed for ring-based interaction? Relevant sub-topics contrast designer-defined gestures [4,15,66,91] and user-defined commands [23,31,52].

RQ_3: What measures have been used to evaluate system and user performance with ring gesture input?

The answer to RQ_1 structures contributions in ring gesture sensing and recognition. The answer to RQ_2 delivers an overview of the types of ring gestures proposed by prior work, from which practitioners can draw inspiration for their prototypes. And RQ_3 focuses on how to evaluate user performance with ring-based gesture input. To answer these questions, our method consists of three steps and corresponding tools:

(1) *Systematic literature review (SLR).* As a first step, we conduct a systematic review of the scientific literature on ring gestures. Conducting SLRs is not the same as reviewing literature: whereas the latter involves selective discussion of the literature on a specific topic to support a new work, SLRs are comprehensive syntheses of the available evidence on the specified topic—methodical, comprehensive, transparent, and replicable [99]. This step enables us to understand what has been achieved in gesture input with ring devices.
(2) *Compilation of a dictionary of gesture-to-function mappings for ring input*, e.g., rotate the ring across the finger to navigate a 1D menu [4] or tapping on the ring with the thumb to confirm selection [11]. This step synthesizes knowledge, currently dispersed in the community, to support design and engineering of future gesture-based UIs for ring devices.
(3) *Development of a web-based tool* to render the findings and resources from this work actionable for researchers and practitioners and to actively support new developments.

4 A REVIEW OF RING GESTURE INPUT

We describe in this section the design and implementation details of our SLR study and present our findings.

4.1 Study Design and Implementation

There are two ways to conduct SLRs, i.e., *quantitative* when they provide meta-data analysis and *qualitative* when taking the form of narrative reviews [99], and it is important to understand the differences between the two approaches to inform the most appropriate design for our study. On one hand, meta-analyses are useful to present numerical data on aspects of interest from the surveyed literature, e.g., in our case to what extent SVMs have been employed as the recognition algorithm of choice to classify ring gestures, or to what extent mid-air gestures performed with the finger wearing the ring have been employed in interactive systems. On the other hand, a narrative review is useful to link studies conducted on different topics to support the interconnection of their findings [7], e.g., in our case this means connecting prior work that used ring devices for different purposes, such as control of home appliances [48], studies focused on gesture set design [31], and gesture recognition algorithms [20]. In this work, we aim for the benefits of both approaches: we report statistics about aspects relevant for the design and engineering of ring UIs (research questions RQ_1 to RQ_3) at which we arrive with the instruments of meta-analysis. But we also support interconnection of various types of contributions on ring-based gesture input, at which we arrive with the tools of narrative reviews. Next, we describe the steps of our SLR with the *identification*, *screening*, and *eligibility* of the relevant literature.

4.1.1 Identification. We followed recommendations from Siddaway *et al.* [99] on how to conduct SLRs to identify relevant references: search at least two different databases, use unambiguous search terms, select search operators, and consider the parts of the articles in which to search for keywords. We selected the ACM DL, IEEE Xplore, SpringerLink, DBLP, and Google Scholar as electronic databases to identify work on ring gestures. After conducting a few exploratory searches to become familiarized with the literature, we found that searching for the words "ring" and "gesture" just in the paper titles would exclude relevant references, while searching in all of the text would include too many nonrelevant ones, so we compromised and searched the abstracts. For instance, we ran the query "[[Abstract: "ring"] OR [Abstract: "rings"]] AND [Abstract: gesture*] AND [Publication Date: (* TO 12/31/2020)]" in the ACM Guide to Computing Literature and found 58 results. In IEEE Xplore, we found 35 references; in SpringerLink, 36; and in DBLP, 23. One paper identified from SpringerLink was a 2013 survey by Rissanen *et al.* [92] that discussed sixteen UI concepts utilizing the form factor of a ring. Thus, we decided to examine the list of references from Rissanen *et al.* (a total of 32), but also the papers that cited it, which we identified using Google Scholar (13 references). This approach led us to discover another survey from 2015 on FADs [98], which included a discussion on rings, and we performed the same procedure to extract the list of references (183) and citations (39). Overall, we compiled a total number of 419 references that went into the screening stage, described next.

4.1.2 Screening and eligibility. We screened the results to remove duplicates and read the abstracts to determine whether the papers were relevant for the topic of gesture input with rings. For example, from the 58 results from the ACM DL, we removed 19 that were off-topic, e.g., papers with the word "ring" part of their abstracts that referred to other topics of investigation, such as haptic feedback using air vortex rings [39]. We formulated the following eligibility criteria (EC) for the references that passed the screening stage:

EC_1: *Availability of full text.* The full text must be available and the paper must be written in English.

EC_2: *Peer-reviewed references only.* The work must be academic and peer reviewed. This criteria includes papers published at conference tracks (e.g., full papers, notes, late-breaking results, etc.), journal articles, but also dissertations (that are reviewed by the members of the thesis committee). We excluded magazine articles, brochures, white papers, presentations, and web sites of commercial smart rings, e.g. [70,82].

EC_3: *Distinguishability.* When the findings of the same study were published by the same authors progressively in different

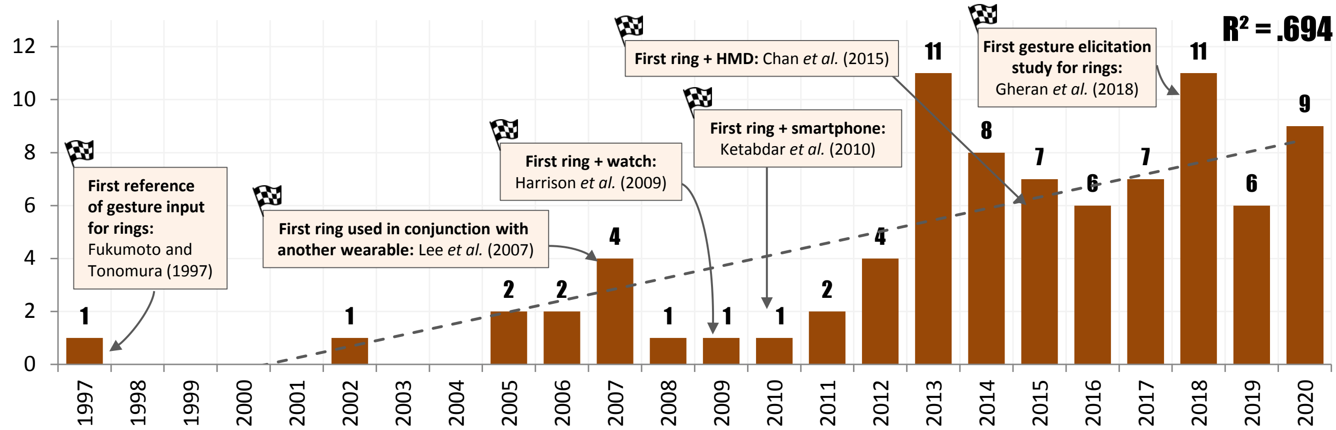


Figure 2: Number of scientific papers identified in our SLR (N=84), shown per year. Notable milestones are highlighted, such as the first ring used in conjunction with a smartwatch [42] or the first gesture elicitation study conducted with rings [31].

forms, e.g., first as a poster and then as a full paper or journal article, we considered only the more extended form of the work and excluded the others. We adopted this approach to avoid reporting inflated statistics in our meta-analysis, e.g., had we considered both the poster and the full article of Colley *et al.* [22,23], we would have reported larger frequency statistics for the gesture types described in those papers.

EC$_4$: *Specificity to rings.* In some cases, the prototypes had a ring form factor, but the authors did not refer to them as rings, but rather as a different kind of device, e.g., a glove [61,127], or the authors explicitly excluded the ring option, e.g., *"compared to other finger-worn control devices such as [...] a ring device [...], FingerPad places no constraints on the fingertip, finger, and hand"* [64, p. 35]. We excluded such papers from our analysis. However, we included multiform-factor prototypes that could also take the form of a ring and the authors explicitly mentioned this possibility, e.g., *"There are a number of ways which the device could be affixed to the finger. It could be embedded on a ring or thimble"* [124, p. 149]. By employing this eligibility criterion, we were able to identify three types of ring devices—*rings, ring-like,* and *ring-ready* (see definitions in Section 2 and examples in Subsection 4.2.3).

EC$_5$: *Specificity to gesture input.* We are interested in our SLR in work about ring gestures (definition in Section 2). Papers that only described a ring prototype, but did not discuss gesture input, were excluded, e.g., we excluded FingerReader [97], but included its second version, FingerReader 2.0 [11] that, unlike the former, integrated a touchpad. We equally also excluded rings designed for feedback only, e.g., Pygmy [84].

After the screening and eligibility stages, we arrived at a set of 84 peer-reviewed papers for our analysis.

4.1.3 Relation to other surveys.

It is important to understand the distinction between our SLR and two prior surveys [92,98] published in 2013 and 2015, respectively. Rissanen *et al.* [92] overviewed 16 UI concepts for rings and focused on the interaction characteristics of ring input, e.g., socially acceptable, subtle, and natural. The overlap between our work and Rissanen *et al.*'s is of 10 papers, representing 10/84=11.9% of the papers included in our analysis, i.e., [4,6,28,29,42,44,45,56,57,59] (the majority of the work on ring gesture input was published after 2013; see Figure 2). Shilkrot *et al.* [98] discussed a variety of finger-augmentation devices (including rings, distal addenda, finger sleeves, thumb devices, gloves and devices for the palm, etc.) and focused on their form factors, input and output modalities, and applications. Since these goals are different than ours, there is an overlap of just 26 references between our survey and Shilkrot *et al.*'s, representing 26/84=30.9% of the papers that we analyzed, i.e., [4,13,16,18,28,29,42–44,47,51,56,59,73,74,77,80,83,85,90,92,101,114,118,120,124]. Moreover, a percent of 55% of the papers from our SLR were published starting with 2015 (Figure 2), the publication year of Shilkrot *et al.*'s [98] survey on FADs.

4.2 Results

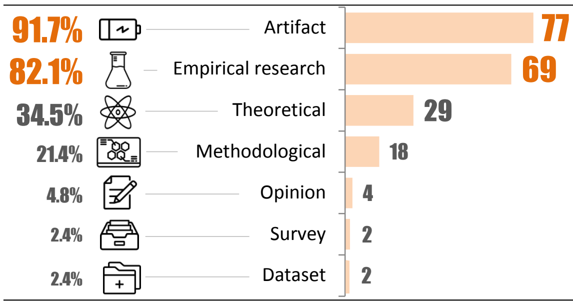
In the following, we report results from a meta-analysis conducted on the set of 84 eligible papers identified in our SLR, followed by a qualitative analysis of the ring gestures described in those papers.

4.2.1 Topics and types of contributions.

To form a preliminary understanding of the topics and contributions of the prior work on ring gesture input, we performed a frequency analysis of the words from the paper titles.[2] Table 1, right lists the top-10 keywords in descending order of their frequency. We found that the words "ring," "finger," and "gesture" appeared with the highest frequency, but authors also preferred to describe their contributions using the words "device" (28.9% of the titles), "input" (20.5%), and "wearable" (18.1%) to highlight specific aspects of their works. Ten papers had the word "recognition" and seven the word "sensing" in their titles. Table 1 also lists associated keywords and correlation coefficients obtained with a document-term matrix analysis,[3] e.g., "finger" was associated with "tracking" [68,113], "input" with "subtle" [4], and "finger-worn" with "device" [20,48,80,133,134].

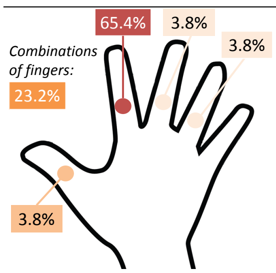
[2]Using the R packages `tm` (https://cran.r-project.org/web/packages/tm) and `SnowballC` (https://cran.r-project.org/web/packages/SnowballC).
[3]Computed using the `findAssoc(..)` function of the R library `tm`; see https://www.rdocumentation.org/packages/tm/versions/0.7-7/topics/findAssocs.

Table 1: *Left*: distribution of contribution types, according to the categories of Wobbrock and Kientz [115], made by the 84 papers analyzed in our SLR. *Right:* top-10 keywords appearing with the highest frequency in the titles of these papers.



	Keyword	Freq.	%	Word associations
1.	ring	49	59.0	subtle (.30), multi-touch (.30)
2.	finger	38	45.8	magic (.40), tracking (.32)
3.	gesture	29	34.9	recognition (.49), tag (.36)
4.	device	24	28.9	large (.48), ring-shaped (.48)
5.	input	17	20.5	subtle (.32), multi-touch (.32)
6.	wearable	15	18.1	computing (.36), application (.36)
7.	interaction	13	15.7	around-device (.40), technique (.40)
8.	recognition	10	12.0	gesture (.49), accurate (.32)
9.	finger-worn	7	8.4	device (.39), accurate (.36)
10.	sensing	7	8.4	capture (.36), active (.36)

Table 2: Frequency of ring devices designed to be worn on various fingers.



Worn on finger(s)	Freq.	%	References
index	51	65.4	[8,9,11,12,19,20,24,28,31–34,36,38,40,42,43,45–49,51,59,66–69,73,74,77,79,80,83,90,93,96,101–103,109,111,112,114,120,123–126,130,133]
thumb	3	3.8	[91,128,129]
middle finger	3	3.8	[13,86,113]
ring finger	3	3.8	[4,50,56]
index, middle, and ring	2	2.6	[6,37]
index and middle	2	2.6	[57,118]
other combinations†	14	18.0	[15,16,18,23,29,35,44,55,65,76,85,87,119,132]
not specified‡	6	–	[21,30,92,98,121,134]
Total	**84**	**100**	

†This category groups other combinations of fingers (frequency=1); ‡The references included in this category did not describe the ring device or there was no information in the paper about the finger(s) on which the ring was meant to be worn. *Note:* the denominator of the percents shown in the "%" column excludes the "not specified" category, e.g., 51/(84-6)=65.4%.

To understand better the contributions made by this prior work, we employed Wobbrock and Kientz's [115] seven categories of research contributions in HCI: empirical research, artifact, methodological, theoretical, dataset, survey, and opinion. On average, the papers from our dataset made between 1 and 4 contributions (M=2.4, SD=0.8). The most frequent contribution was *artifact*, which we identified in 77 of the 84 papers (91.7%), followed by *empirical research* (69/84 =82.1%) with high association, i.e., artifacts were evaluated in 66/84 =78.6% of the cases; see Table 1, left. We found two *surveys*: Shilkrot *et al.*'s [98] on FADs and Rissanen *et al.*'s [92] overview of UI concepts for rings (see Subsection 4.1.3 for a comparison to our SLR); and four papers with *opinion* contributions: Gheran *et al.* [30] on smart rings for users with motor impairments, Rissanen *et al.* [92] on subtle and natural UIs, Wolf [118] on ubiquitous grasp interfaces, and Gheran and Vatavu's [32] examination of possible uses of rings for in-vehicle and outside-the-vehicle input. Only two papers [31,112] made *dataset* contributions (2/84=2.4%).

4.2.2 Fingers wearing the ring. Most of the papers that we surveyed used one ring and fifty-one (65.4%) specified the index finger. A few papers described prototypes with multiple rings for two fingers, e.g., the index and the middle [57,118], three fingers—index, middle, and ring [37], or various finger combinations [16,18,23,65]; see Table 2. The number of fingers addressed by the ring devices from the prior work varied between 1 and 5 (M=1.27, SD=0.74, Mdn=1).

4.2.3 Rings, ring-like, and ring-ready devices. Due to the variety of finger-augmentation prototypes presented as rings in the scientific literature, we distinguish among three categories of such devices: devices with a ring form factor or *rings* for short, *ring-like*, and *ring-ready* devices; see definitions in Section 2. We found sixty-five prototypes (79.3%) with a ring form factor, eight (9.7%) with different form factors but enabling gestures as rings from the first category, and nine ring-ready devices (11.0%) that, among the multiple ways in which they can be worn, afford the ring option as well; see Table 3.

Ring-like devices are not self-contained by the ring form factor, i.e., they require instrumentation of other parts of the finger. Thus, ring-like devices can deviate from the aspect of a ring form factor, although they enable the same kind of interactions as rings from the first category. An example of a ring-like device is Stetten *et al.*'s [103] "Fingersight" prototype that uses a video camera mounted on the distal phalanx and a cell phone vibrator on the medial phalanx of the index finger, representing a novel device covering a large portion of the finger to decouple sensing (on the distal phalanx) from feedback (medial phalanx). Similarly, Stearns *et al.*'s [102] "TouchCam" employs sensors that need to be positioned at different locations on the wearing finger, i.e., the IR reflectance sensors go on the two sides of the fingertip and a video camera and IMU sensor on the proximal phalange, with a design consisting of three rings worn on the same finger. A previous version [101] placed a video camera and vibration motors at different locations on the wearing

Table 3: Frequency of ring, ring-like, and ring-ready devices in the papers analyzed in our SLR.

Category	Description	Ring form?	Freq.	%	References
Ring	Finger-worn device with a ring form factor	Yes	65	79.3	[4,8,9,11–13,15,19,20,24,29–38,40,42,43,45–49,51,55–57,59,65–69,73,74,79], [80,83,85–87,90,91,93,96,111–113,118–121,123,126,128–130,132–134]
Ring-like	Device worn on the finger that deviates from the form factor of a ring, but enables similar input as rings from the first category	No	8	9.7	[6,16,28,76,101–103,125]
Ring-ready	Multiform, multi-purpose device that, among several form factors, can also take the form of a ring and be used as such	Can be	9	11.0	[18,21,23,44,50,77,109,114,124]
		Total	**82**†	**100**	

†Two papers were surveys [92,98].

finger. In other prototypes [28,76], the sensors from the ring do not work independently, but rather as part of a larger device that covers more than the finger area. For example, the rings from Moschetti *et al.*'s [76] prototype need an additional sensor to be worn on the wrist and the back of the hand for the device to operate. In Fukumoto's [28] finger-ring shaped wearable handset, the ring is only a part of the handset that also requires a microphone to be attached to the wrist. These examples that deviate from the form factor of a ring, simply because they require parts that are not self-contained by the form factor of the ring, while the ring remains central to the device, are *ring-like* in our taxonomy; see Table 3 for the eight prototypes that we identified in the literature.

Ring-ready devices are finger-worn, but can also be worn on other body parts and/or used in other ways than a ring. Therefore, they are multi-form, multi-purpose devices that, among their multiple possible forms and uses, can also take the form of a ring and be worn and used as such. For example, Cheung and Girouard [21] employed a magnetic ring to interact with a smartphone, but instead of asking the user to wear the ring, the authors focused on and evaluated a different use case where the ring device was held between the fingers. Ketabdar *et al.* [50] adopted a similar approach and demonstrated multi-purpose functionality for rings that can be either worn or held between the fingers. Colley *et al.* [23] proposed interactions for rings that are placed on a surface, e.g., interactions that involve turning over the ring and rotating it on the surface. Other authors were explicit about the multi-form and/or multi-purpose functionality of their devices, e.g., "*the receiver is by default embedded in a minimally-intrusive ring form factor for finger touch, but may also be embedded in other everyday devices such as pens or mobile phones for using them as a pointing tool on the body*" [77, p. 192]; the "DeformWear" prototype of Weigel *et al.* [109, p. 28:5] can take the form of a ring, a bracelet, and a decorative pendant as multiple ways to wear and use it; "zSense" [114] enables integration in devices with various form factors, from smartwatches to smartglasses and smart rings; and the "Magic inger" prototype of Yang *et al.* [124] enables *"a number of ways which the device could be affixed to the finger. It could be embedded on a ring or thimble"* (p. 149). All these examples denote *ring-ready* devices that can be worn and/or used in various ways, not just as rings; see Table 3 for the nine prototypes that we identified in the literature.

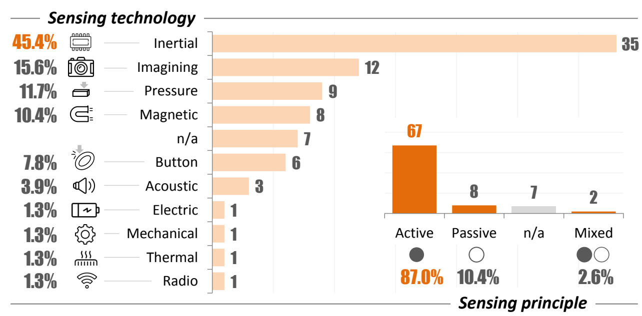


Figure 3: Sensing technology (left) and sensing principle (right) to detect gestures performed with ring devices.

4.2.4 *Gesture sensing.* We used the following ten categories, inspired and adapted from Shilkrot *et al.* [98] to classify gesture sensing technology used for ring devices: acoustic, button, electric, inertial, imaging, magnetic, mechanical, pressure, proximity, and radio. We found that inertial sensing was the most common approach among the 77 prototypes that detailed the sensing method (35/77=45.4%) followed by imagining (15.6%), pressure (11.7%), and magnetic sensing (10.4%), respectively; see Figure 3. However, it is important to note that sensing techniques improve and advance with time and, while Figure 3 represents a photograph of the most popular techniques so far, new approaches will appear in the future. Thus, we propose another criterion to discriminate between gesture sensing approaches with rings. We use *active sensing* to denote rings with embedded sensors, e.g., accelerometers or gyroscopes [20,76,93,133,134], while we use the term *passive* to refer to the situations when the ring is tracked by an external sensor, such as a video camera [49,56], a magnetometer [21,24,50,86,91], or an RFID reader [6]. We majoritarily found rings from the first category (67/77=87.0%), eight devices (10.4%) were passive, and two prototypes (2.6%) were both active and passive [6,18], i.e., they embedded sensing but an external device was also used.

4.2.5 *Gesture recognition.* Seventy papers (83.3%) from the set identified in our SLR addressed gesture recognition. Some of the

Table 4: Techniques employed for the recognition of ring gestures.

Recognizer	Freq.	%	References‡
Support Vector Machine (SVM)	14	13.9	[12,24,36,65,67,76,77,86,93,102,114,129,130,132]
K-Nearest Neighbors (KNN)	11	10.9	[24,47,55,65,111,112,119,126,128,132,134]
Dynamic Time Warping (DTW)†	8	7.9	[68,69,111,112,119,121,123,128]
Decision Tree	6	5.9	[24,47,50,65,76,93]
Naive Bayes	4	4.0	[24,47,93,132]
Random Forest (RF)	4	4.0	[15,24,119,132]
Hidden Markov Model (HMM)	3	2.9	[20,68,133]
Multilayer Perceptron (MLP)	3	2.9	[12,50,93]
Long Short-Term Memory (LSTM)	2	2.0	[20,113]
Other approaches (frequency=1): AdaBoost, Bayes Network, Finite State Machine, Gesture Decomposition and Similarity Matching, Linear Regression, Logistic Regression, Pearson correlation coefficient, Probabilistic Neural Network, Sign Sequence Template Matching	9	8.9	[19,24,49,65,91,114,121,121,132]
Other approaches: ad-hoc, mostly threshold-based implementing various rules and measurements	24	23.8	[4,6,8,18,21,24,24,35,40,42,45,47,48,57,59,74,84,87,96,109,118, 120,124,125]
Touch/tap detectors (various approaches, including buttons)	13	12.9	[9,11,13,16,28,34,43,46,66,73,80,85,90]
Total	**101**	**100**	

†Includes Lucky Time Warping [112]; ‡References that implement multiple techniques are reported repeatedly.

approaches fed the sensor readings (e.g., linear acceleration) directly to the gesture recognizer, while others extracted or computed specialized features. The K-Nearest Neighbor (KNN) technique with a dissimilarity function, such as Dynamic Time Warping (DTW) [68,119,123,128], is a representative example of a gesture recognizer of the first kind. Other approaches computed various features, e.g., HAAR [49], average jerk [121], energy and entropy [134], frequency-based features [93], etc., and some techniques [50] employed sliding windows on the time series of the raw sensor readings in order to compute the features. The feature values were then fed to a machine learning model, e.g., SVM [36,77,86] or Random Forest (RF) [15,119]. Some papers employed a large number of features, e.g., Chan *et al.* [15] used 2,000 candidate features for their RF classifier. Finally, a few papers implemented rule-based approaches involving thresholds applied to the sensor readings, e.g., acceleration [35,45,87], finger tilt angle [6,18], or ring rotation [21,40]. Table 4 shows details regarding the popularity of conventional classifiers, e.g., SVMs, KNN, HMMs, etc., employed by prior work. Just like our previous mention regarding gesture sensing technology, it is important to note that recognition techniques advance and improve constantly and, while Table 4 represents a photograph of the most used techniques by prior work on ring gesture input, new approaches are likely to become more popular in the future, such as those based on deep learning network architectures [20,113].

Besides papers employing machine learning techniques for ring gesture recognition, we found thirteen papers [9,11,13,16,28,34,43, 46,66,73,80,85,90] implementing ring gestures in the form of presses, taps, and touches on the ring surface detected by physical buttons and touchpads. Finally, we found two papers with Wizard of Oz studies that did not implement any actual gesture recognizer, but users (study participants) believed there was one [31,37].

4.2.6 User studies. Eleven papers from the 84 examined in our SLR did not conduct studies with users and five did not report the number of participants. The rest reported studies with numbers of participants between 1 and 92 (M=16.8, SD=15.6). A percent of 30.9% of all the user studies had less than 10 participants, 55.9% between 10 and 30, and 9 studies involved more than 30 participants. We found eight papers addressing users with visual impairments [11, 67,77,79,80,85,101,102], two addressing deaf and hard of hearing persons [55,69], one for people with Raynaud's phenomenon [87], and one opinion paper reflecting on the opportunity of designing smart ring applications for people with motor impairments [30].

4.2.7 Evaluation measures and methods. Sixty-five papers (77.3%) employed various types of measures to evaluate system performance (e.g., classification accuracy) or user performance (e.g., task completion time) with ring gesture input. Overall, we counted 192 measures, of which 61 were distinct; see Table 5 for details. Classification accuracy was the most frequent measure employed by 37 of the papers that we surveyed, followed by free-form user feedback (22), confusion matrices (21), and task time (15), respectively.

4.3 Ring Gestures

We extracted a total number of 954 gestures from the 84 papers identified in our SLR, of which 579 gestures were distinct. We classified the gestures according to the following categories:

(1) *Tap and touch input.* Gestures from this category include tapping on a touch sensor located on the ring [11,12,34], pressing a physical button on the ring [8,9,13,43], multitouch input on the ring [66], but also tapping on fingers [28,45], on the body [85], and on surfaces [29,86,132].
(2) *Swipes and stroke-gesture input* represent movements of the finger wearing the ring on a surface, e.g., drawing a "question mark" symbol. Strokes can be performed on the ring [34], on fingers [15], on the other hand [85], on the body [77,102], or on other surfaces [36,101,124].
(3) *Free-hand and mid-air gestures* represent poses adopted by the hand wearing the ring [15,48], finger movements [91,112,

Table 5: Evaluation measures employed for system and user performance with ring gesture input.

Evaluation Measure/Method	Freq.	Percentage§
Classification accuracy [12,15,19,20,24,36,40,42,47–50,65–69,76,77,86,91,93,102,111,112,114,119,121,123,124,126,128–130,132–134]	37	19.3%
Free-form feedback (e.g., interviews, brainstorming, elicitation, etc.) [4,11,12,19,23,31,37,38,40,43,56,65,67,73,74,80,85–87,101,102,126]	22	11.5%
Confusion matrix [12,15,24,40,46,50,65,67,69,86,93,102,111,112,114,121,128–130,132,134]	21	10.9%
Task time [9,11,19,21,29,42,44,46,74,77,101,109,120,125,126]	15	7.8%
Error rate‡ [4,46,51,69,109,112,126]	7	3.6%
Classification time [77,102,119,123,133]	5	2.6%
NASA TLX [9,12,38,46,126]	5	2.6%
Other measures (frequency > 2): Overall preference [21,80,85,87], Perceived difficulty [12,23,66,85,101,130]†, Input speed [35,38,80], Movement time [4,51,126], Perceived effort [80,120,125,130]		
Other measures (frequency ≤ 2): Absolute error [18,113], Error count [9,46], Gesture production time [12,126], Gesture type [30,33], Number of attempts [11,40], Perceived comfortability [6,130], Perceived fun [11,12], Perceived helpfulness [11,80], Perceived usefulness [23,125], SUS [11,12], Willingness to wear the ring [125,130], Agreement rate [31], Angle of arm during input [86], AttrackDiff [23], Average absolute vertical distance from the line center [101], Corrected error rate [38], Creativity [31], Difficulty in learning [37], Effective width [4], Energy harvesting and consumption rate [36], Gesture offset error [120], Gesture similarity [20], Hint rate [37], Learning curve [48], Mental effort [37], Motor skill [31], Operational efficiency [48], Perceived satisfaction [11], Perceived appearance (form factor) [80], Perceived ease of recognizability [40], Perceived efficiency [6], Perceived frustration [12], Perceived hands-free operation [80], Perceived input speed [130], Perceived naturalness [21], Perceived physical comfort [85], Perceived speed [11], Perceived success [37], Pointing style [11], Reaction time [91], Recall rate [37], Response time [40], Social acceptability [85], Success rate [11], Thinking time [31], Throughput [51], Tracking accuracy [18], Uncorrected error rate [38], User experience questionnaire (UEQ) [21]		

†"Perceived difficulty" and "Perceived ease of use" could also be grouped together; ‡Error rate and classification accuracy are interchangeable; §Computed with the denominator 192 (the total number of measures identified in our set of surveyed papers), e.g., 37/192=19.3%.

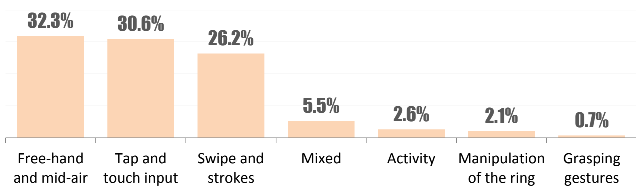


Figure 4: Frequency of ring gesture types (percents computed from 954 gestures extracted from 84 papers).

113], pointing [18,38,44], or movement of the hand in space, such as around a smartphone [21,42,124].

(4) *Grasping gestures* depict interactions with objects [118,120].
(5) *Manipulation of the ring* includes gestures that change the ring position, orientation, or location [4,23,40].
(6) *Mixed category* includes gestures that combine characteristics of the previous categories, e.g., combining hand poses with touch input [65] or shearing and pinching a ring made of deformable material [109].
(7) *Activity.* A few papers [47,76] employed the ring to infer user activity, such as walking, eating, sleeping, etc. Since activities are different from gestures, we considered this category for completeness purposes only.

Figure 4 illustrates the frequencies of the gesture types employed for ring input in the scientific literature. The largest category is free-hand/mid-air gesture input (308/954 =32.3%) followed by tap and touch input (30.6%) and swipes and stroke-gestures (26.6%). There were only 20 gestures involving manipulation of the ring (2.1%) [4,23,40] and 7 grasping gestures (0.7%) [77,118].

4.3.1 Gesture sets. On average, the size of the gesture sets used in the papers that we surveyed varied between 1 and 100 (M=11.9, SD=14.9). However, some outliers were present: Liu *et al.* [68] introduced a technique to recognize 100 American Sign Language (ASL) hand poses and gestures, Fukumoto and Tonomura [29] presented a system with 52 tap chord sequences, and Chatterjee and Matsuno [16] reported a technique consisting of 46 sequences of taps on the index finger. To remove the effect of these outliers for a more representative characterization of central tendency, we computed the 20%-trimmed mean and found an average of 8.1 gestures ($CI_{95\%}$=[5.81,10.39]), very close to the median (Mdn=8).

4.3.2 Rings used with other devices. Most of the papers that we examined employed rings as input devices to control other systems, such as home appliances [31,48], and some papers described rings to control content displayed on other devices, such as smartwatches [24,42,91,109], smartphones [21,50], HMDs [15,109], or a Braille device [79]. In some of the systems, the other device was not controlled, but rather provided visual feedback for the action effected with the ring, such as a display worn on the wrist [59]. In these examples, the ring device acts as a mere controller for the other, primary device. However, a more interesting role for the ring is when its input capabilities are combined with those of another device for cross-device interaction. To this end, we distinguish the following use cases: (i) the ring brings *supplementary* capabilities, but of the same kind as those provided by the other device and (ii) the ring brings *complementary* capabilities to the multi-device system. Regarding the former, Liu *et al.* [68] employed a smartwatch and a ring for an application involving ASL translation, and Yeo *et al.* [126] demonstrated macro-micro pointing on a large display with input sensed by a watch and a ring. In the second category, we identified five papers: Lim *et al.* [65] explored gestures detected by a ring (hand poses and finger motions) and a tablet (touch and multitouch); Sei *et al.* [96] examined a vocabulary of combined touch input on the smartphone and postures and gestures of the index finger of the hand holding the smartphone; Park *et al.* [86] demonstrated identification of the finger wearing the ring when in contact with the smartwatch; Gheran *et al.* [33] specified bimanual interactions with rings worn on both hands; and Bianchi *et al.* [9] used a ring device for on-body input.

5 GESTURING, A WEB-BASED TOOL FOR RING GESTURES

We capitalize on the results of our SLR to propose a tool to assist researchers and practitioners interested in designing gesture input for ring devices. Our tool, GestuRING, is freely available at the web address http://www.eed.usv.ro/~vatavu/projects/GestuRING, and features the following functionality (see Figure 5 for screenshots):

(1) Access to a dictionary of 579 mappings between ring gestures and system functions for interactive applications, extracted from the 84 papers from our SLR; see Section 4.3. Descriptions of gestures are available in JSON, which we chose for its lightweight structure accessible to humans and machines alike; see Figure 5, right. The dictionary can be queried online via the web UI or downloaded for offline processing.
(2) Queries can be performed on the dictionary by entering keywords that specify characteristics of the target gesture (e.g., "thumb" or "swipe"), the function (e.g., "copy," "photo," "next"), or the device to control (e.g., "TV").
(3) We also provide a YouTube library of video recordings of the gestures from our dictionary[4] to demonstrate the gestures; see Figures 1 and 5. The videos are linked to the entries from our dictionary and readily accessible following a query.
(4) We recorded a gesture dataset using a 3-axis accelerometer (Phidgets MOT1100,[5] attached to a 3D printed ring worn on the index finger); see Figure 5 for a screenshot of a gesture represented with acceleration signals. This dataset enables practitioners to access ring gestures stored in a computational form, compare gesture representations, and engage in preliminary analyses with actual data in order to inform their prototypes, gesture sets, or their own, more elaborate data collection procedures.

GestuRING features a large amount of information that is readily available to inform design decisions about which ring gestures to use to effect which function in an interactive system or to inspire new gesture designs by building on a body of scientific knowledge that is systematically structured. Specifically, GestuRING presents users with gesture descriptions, associated system functions to effect, detailed text characterization of the gestures, the gesture category (e.g., touch, mid-air, stroke, etc., as per Figure 4), and links to the YouTube video library and the recorded ring gesture dataset. In the following, we illustrate possible use cases of GestuRING with several practical examples.

Consider a practitioner interested in designing a ring gesture set to control devices in a smart environment, e.g., turn the lights on and off, change to the next channel on the TV, and control the volume of the ambient music. The practitioner can use GestuRING to browse the gesture dictionary to become familiarized with various associations between ring gestures and system functions, such as gesture commands that have been previously proposed to turn devices on/off, increase and decrease the sound volume of selected devices, navigate through lists, and so on. For example, the practitioner discovers that rotating the hand wearing the ring to the left has been previously used to decrease the brightness of the light provided by a lamp, but also to lower the volume of a CD player and TV set [47,48], while an extension of the thumb [91] and a swipe of the thumb across the other fingers [129] have been used to control a music player. Alternatively, the practitioner can run a query by specifying keywords relevant to their application domain, such as "lights," "TV," or "channel." By examining the results returned by the query, the practitioner finds that applying pressure at the top and bottom parts of the ring has been used to change channels in a music controller application [83], which informs them about a new gesture modality—pressure—to consider exploring in their design. GestuRING also accepts queries about gesture types (e.g., mid-air, stroke-gestures, tap input, etc.) and body parts (e.g., thumb, forearm), should the practitioner be interested in narrowing down their results further. (The search box accommodates all these queries since the entered keywords are matched across all of the text data from our database.) Then, the practitioner can watch the corresponding YouTube videos of selected gestures to better understand how those gestures are articulated and whether they are suited for the application domain and the specific context of use. Moreover, direct DOI links to the academic publication where a specific gesture-to-function mapping was discussed enables the practitioner to dive in further to understand better the specific context in which that mapping was originally proposed or technical aspects about a specific ring device, gesture processing, or recognition technique. For example, by further investigating the pressure gesture, the practitioner learns that the solution proposed in [83] involves an Arduino micro-controller and IR sensors, which the practitioner can access easily, while the technique to detect the amount of pressure involves the use of a threshold against which the data from the IR sensors are compared. Based on these findings, the practitioner decides to combine in their prototype input on the ring (via pressure gestures) and motion gestures performed with the ring (e.g., rotating the hand to the left and right). Regarding the latter, the practitioner downloads the two motion gestures to conduct preliminary evaluations, such as the production time of those gestures, or to run a gesture recognition algorithm to see whether the signals of those gestures are discriminable enough using for instance the \$1/\$3 recognizers [54,117], before deciding to conduct their own, more elaborate data collection procedure.

As another example, consider a practitioner that has conducted a usability evaluation of a ring gesture UI and found low preferences expressed by the study participants for the proposed ring gesture interactions. The practitioner engages the participants into a discussion to understand the problems of the ring UI prototype, and finds that some of the mid-air gestures are considered tiring to perform. The practitioner wants to know how this problem has

[4]We omitted activities (see Figure 4), such as running, eating, etc. [47], gestures performed on a deformable ring [109], and hand poses that were not specified in the papers that we surveyed, such as the ASL poses from [68].
[5]https://www.phidgets.com/?tier=3&catid=10&pcid=8&prodid=956

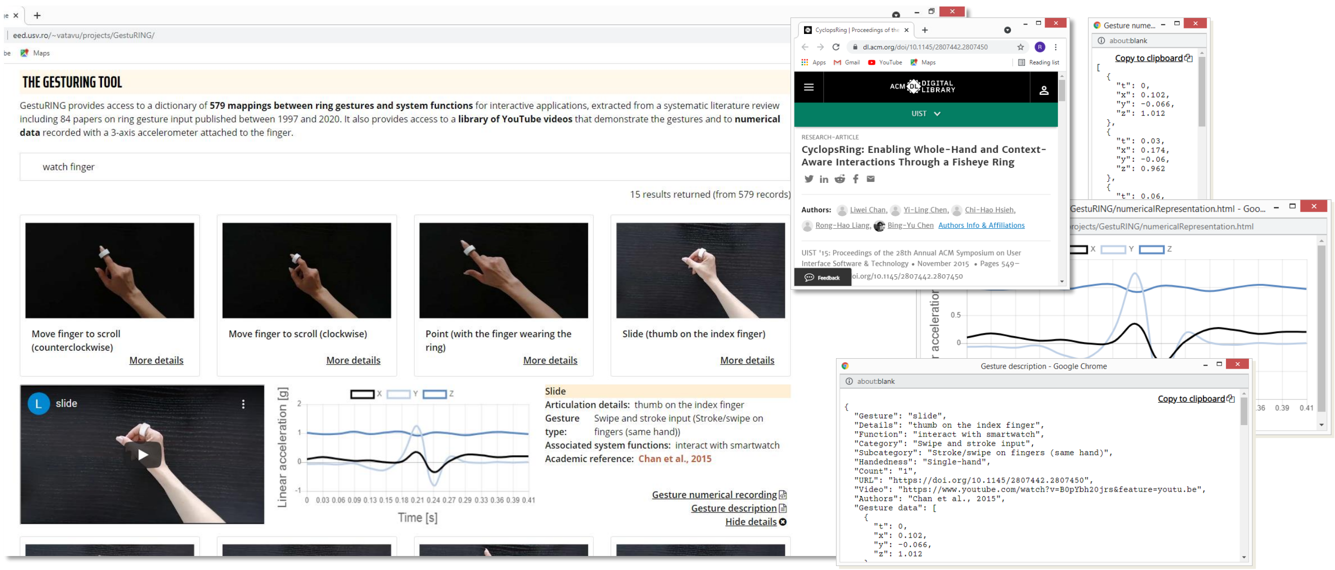


Figure 5: GestuRING features a large searchable dataset of ring gestures with textual descriptions, gesture-to-function mappings, links to scientific references, and a companion YouTube video and gesture data library. GestuRING is available at the web address http://www.eed.usv.ro/~vatavu/projects/GestuRING.

been dealt with for other, similar ring UI prototypes, and runs a query in GestuRING with the keyword "mid-air." By watching the videos of other mid-air gestures, the practitioner can compare gesture designs from prior work to their own. During the investigation of these gestures, the practitioner finds a set of mid-air gestures that seem easy to articulate and decides to look more closely at the linked academic publication. They find Gupta *et al.*'s [37] examination of semaphoric finger gestures, where the problem of fatigue was addressed explicitly, i.e., finger tap gestures performed in mid-air that follow the same style of invocation do not only minimize fatigue, but are also easy to remember and associate to system functions [37] (p. 224). By capitalizing on this knowledge, the practitioner decides to replace some of the mid-air gestures from their initial prototype with variations of mid-air semaphoric gestures informed from [37], and prepares a new user study.

As a final example, consider a researcher interested in understanding the mappings that other researchers have proposed between ring gestures and system functions, and wishes to compare those mappings with the end-users' expectations of intuitive gesture-to-function associations [116]. In other words, the researcher is interested in conducting a replication of Morris *et al.*'s [75] study about designer-created *vs.* user-defined surface touch gestures, but for ring input. To this end, the researcher employs GestuRING to inform their experiment design by browsing and selecting system functions for which associations with ring gestures have been previously proposed in the literature. For example, the researcher discovers that menu operation appears frequently in the previous work on ring gesture input (i.e., the keyword "menu" entered in GestuRING returns 47 results) as does selecting devices and content with rings (i.e., the keyword "select" appears 28 times). Based on this information, the researcher decides to include these system functions in their experiment, which will enable relating their own results and discussing their own findings with respect to previous results reported in the scientific literature. Also, the researcher discovers that other functions, commonly encountered in many interactive systems, such as "copy," "paste," and "delete," appear with low frequency for applications involving ring devices (i.e., just 4, 5, and 5 records, respectively). The researcher decides to investigate possible applications for these system functions and ring devices to understand whether the literature has inadvertently missed such opportunities for ring gesture input. By watching the associated videos and consulting the corresponding scientific publications linked to these system functions, the researcher has fast access to important information to inform the design of their experiment as opposed to the situation in which they would have had to identify the relevant literature by themselves.

6 LIMITATIONS

There are several limitations to our work. First, searching other scientific databases, such as Scopus, or employing other keywords during the search will likely reveal new publications, not covered in our SLR, but relevant for ring gesture input. Also, as technology evolves with time, new gesture sensing and recognition techniques are expected for ring gesture input. Second, our SLR focused on scientific, peer-reviewed work only and excluded commercial products. An interesting follow-up study could compare gesture-to-function mappings from the scientific literature to those actually implemented by commercial ring devices and applications. Third, our tool is primarily intended as a dictionary of ring gestures with the goal to enable easy access to such information and make the findings of our SLR actionable for researchers and practitioners. Our tool does not assist with other aspects that are key for the design and engineering of gesture interaction, for which other specialized tools exist. For instance, the classification accuracy of a specific gesture depends not only on the algorithm (and features, sensors, etc.), but also on the other types of gestures from the gesture set and needs to be interpreted in the context in which it was evaluated. We ask readers to consider this important aspect when using GestuRING to identify gesture-to-function associations to create their own gesture sets. For other aspects relevant to gesture interaction, we refer readers to other tools, such as MAGIC [5,53], GestureWiz [100], GestMan [71], KeyTime [62,63], Crowdlicit [1], GDATK [104], GECKo [3], GHoST [106], Gelicit [72], AGATe [107,108] that deal with gesture elicitation, representation, recognition, and analysis.

7 CONCLUSION

We conducted an analysis of the landscape of contributions on gesture input with ring devices and compiled our findings in the form of a web-based tool with resources about ring gestures. We hope that these resources will foster new work in gesture-based UIs for the versatile family of rings, ring-like, and ring-ready devices towards systematic exploration of the interactive opportunities that this class of finger-worn devices enables for wearable computing.

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