A Descriptive Analysis of a Formative Decade of Research in Affective Haptic System Design

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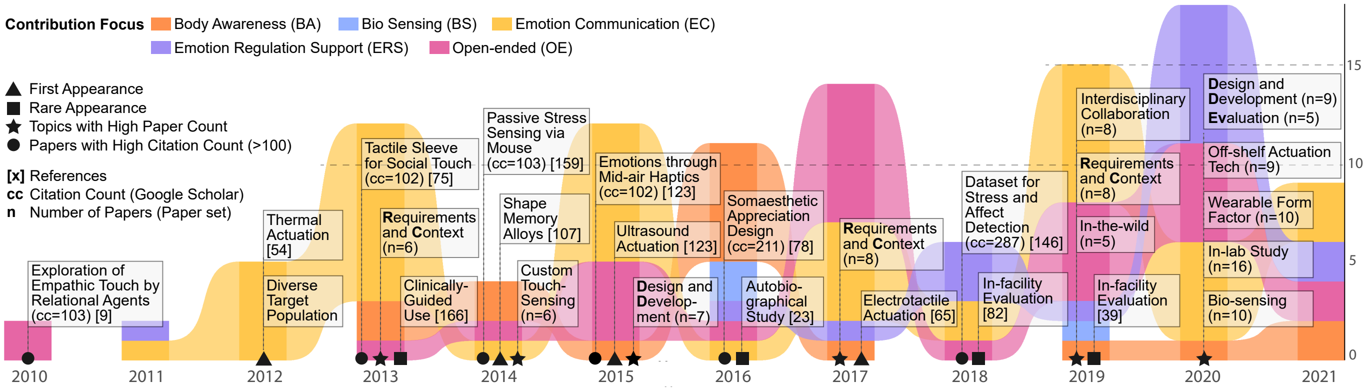

Figure 1: Annotated overview of research trends between 2010–2021 marked with items of special interest. The colored underlay denotes trends in our analysis dimension of Ⓓ Contribution Focus, with publication count on the y-axis.

ABSTRACT

The global pandemic exposed serious drawbacks in relying on communication modalities in which social touch, however important, is absent. Considerable research has explored haptic technologies for sensing or displaying social touch and influencing affective state, for wellness, social communication, emotion regulation, and affect therapy. However, this Affective Haptic System design (AHSD) work varies widely in purpose and origin discipline, making it difficult to perceive overall progress and identify primary obstacles to practical deployment. We conducted a scoping review and conceptual analysis with a design lens, identifying 110 papers from the last decade in 11 ACM and IEEE venues that regularly attract AHSD work. Our analysis identified 38 dimensions within 8 facets: demographic, theoretical grounding, impact, system specification, usage specification, ethical consideration, technology, and evaluation. We visualize trends, disciplinary mixing, and topical focus over time, and highlight major advances while pinning down crucial gaps that can be addressed in the future.

CCS CONCEPTS

• **Human-centered computing → Haptic devices**; *HCI theory, concepts and models.*

KEYWORDS

Emotion/Affective Computing, Touch/Haptic/Pointing/Gesture, Meta-Analysis/Literature Survey, Content Analysis, Affective Haptics

ACM Reference Format:
Preeti Vyas, Unma Desai, Karin Yamakawa, and Karon E MacLean. 2023. A Descriptive Analysis of a Formative Decade of Research in Affective Haptic System Design. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems (CHI '23), April 23–28, 2023, Hamburg, Germany.* ACM, New York, NY, USA, 23 pages. https://doi.org/10.1145/3544548.3580735

1 INTRODUCTION

Affective states such as emotions, stress responses, impulses, and triggers play a significant role in a person's mental health. Early research in neuroscience establishes a bi-directional connection between touch and emotions [60, 112]: emotions can be communicated via touch [71], and emotional state can be altered through touch-based interactions [81]. Although the relationship between touch and emotions has been explored extensively in the fields of neuroscience [94] and social science [40], the study, development, and design of touch-based technology harnessing such a relationship for the betterment of an individual's affective health is relatively new and has particularly accelerated during the last decade [33].

CHI '23, April 23–28, 2023, Hamburg, Germany

ACM ISBN 978-1-4503-9421-5/23/04...$15.00
https://doi.org/10.1145/3544548.3580735

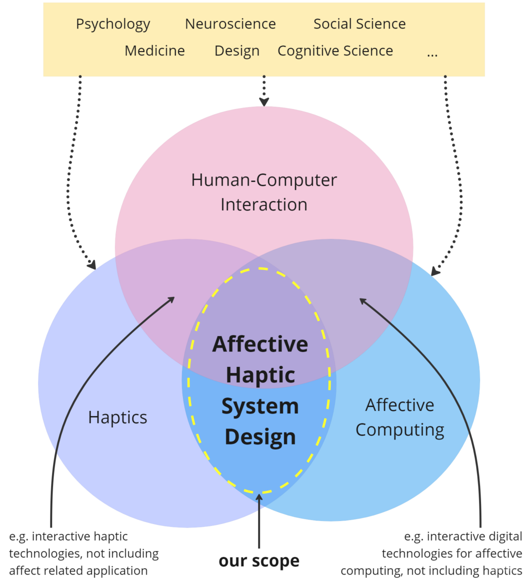

Figure 2: Conceptual Venn Diagram (not to scale) to locate AHSD in the context of Haptics, Affective Computing, and Human-Computer Interaction, with the top bar indicating via directed dotted lines the influence of additional disciplines. In this paper, the three major areas manifest as the primary discipline of our search venues, each of which contains some work with qualities from the other areas. The three-way overlap at the center along with the two-way overlap between Affective Computing and Haptics mark the scope of Affective Haptic System Design, encircled by a dashed yellow ellipse. Excluded overlapping regions are explained through the examples at the bottom.

In 2009, Tsetserukou *et al.* [171] used the term *Affective Haptics* – "the emerging area of research which focuses on the design of devices and systems that can elicit, enhance, or influence the emotional state of a human by means of the sense of touch". Adapting their usage while being mindful of the emerging sensing, computational, and evaluation aspects in current focal topics, we identify *Affective Haptic System design* (AHSD) as a field of research that spans studying, designing, developing, and evaluating systems or technologies that can sense, process, display, elicit, enhance, or influence a person's affective state via touch. We here consider AHSD as a haptics-focused subfield of Affective Computing [135, 136] (Figure 2). This a design-influenced view; there are others, *e.g.*, grounded in social sciences and/or clinical perspectives.

AHSD research spans several disciplines including but not limited to Haptics, Affective Computing, Human-Computer Interaction (HCI), Design, Social Science, Psychology, Medicine, Neuroscience, and Cognitive Science, and is published in a wide range of venues. With diverse methodologies, the investigators publishing on these topics often seek to understand the relationship between touch and emotion using a variety of field-specific perspectives. Systematically analyzing past work at this intersection creates a holistic picture of where current research stands, how it interleaves across contributing disciplines, and where it may lead us in the near future.

Rigourous analysis of the full interdisciplinary breadth of AHSD research would present significant challenges and risk comparing incommensurable factors and drawing misguided conclusions. Hence, in this scoping review, we examined AHSD and its evaluation through the lenses of three disciplinary venues (in Haptics, Affective Computing, and HCI). Distinct but overlapping in focus (Figure 2), they all include design as a primary topic; in haptics and affective computing venues, this has historically been more technical design, while HCI encompasses a broad span (*e.g.*, interaction, envisioning, and contextual study). All three are interdisciplinary and see contributions highlighting other aforementioned fields. We seek to understand how AHSD research is shaped within the context of a researcher's background, their specific design approaches, types of contribution, technologies, methods, and evaluation techniques. Although we review evaluation methodologies and techniques, we do not draw conclusions on the health and well-being-related outcomes of such work. With a scoping review and a conceptual analysis of AHSD research within Haptics, Affective Computing, and HCI venues, we contribute:

1. A dimensional framework within which we can analyze past and future research in Affective Haptic System Design;
2. A descriptive analysis of over a decade of research projects systematically sourced from key contributing venues;
3. Identification of major advances and open challenges in the field as opportunities for future researchers.

2 BACKGROUND

While our focus lies at the *intersection* of Haptics, HCI, and Affective Computing (as represented by communities and venues with these foci), this review should be understood through a perspective *centred* in each of these three fields. In this section, we unpack the bigger picture of this interdisciplinary collation. By discussing past review articles in the context of these three disciplinary foci, we aim to situate this paper within a larger discourse.

Haptics Lens: We identified four review papers situated close to our work. Van Erp *et al.* (2015) [177] covered the importance of social touch and its relation to physiological responses, models of trust, affect, and pro-social behaviour, whereas Huisman (2017) [74] reviewed the haptic technologies used for social touch and the complexities involved in developing such systems. In both, the defined scope includes mediated social touch and its application in information communication technologies, which we see as an essential part of AHSD research. However, this is far from the whole picture as will become clear. Eid *et al.* (2016) [33] discussed direct and mediated emotion communication via haptic channels applicable to inter-human and human-robot social interaction, a prominent contribution focus of AHSD research before 2016.

Thereafter came the inclination of AHSD research towards diverse foci, including emotion regulation support, body awareness, and bio-sensing (Figure 1). More recently, McDaniel *et al.*'s (2020) chapter [101] covers a broader ground, showcasing research and commercial efforts towards therapeutic haptic technologies from 1980-2019, providing an overview of AHSD research targeted to therapeutic applications within themes like games, toys and play, emotion regulation, stimulation therapy, distributed touch therapy, and haptics for social wellness.

Building on these topical reviews but taking a more holistic approach, we attempt to organize and analyze existing AHSD literature in greater breadth (in terms of diverse contribution focus) and depth (in terms of analysis).

HCI Lens: We found broadly-scoped review papers involving haptics as just one of the multiple interaction modalities. Sanches *et al.* (2019) [145] explored the research design space of HCI and Affective Health with a focus on ethical approaches and clinical evaluation. Their scope was broad with respect to areas within HCI (sparsely covering haptic literature), and narrow in chosen venues (only SIGCHI proceedings), hence not directly relevant to our scope but helpful methodologically.

Other notable but more specific HCI reviews with relevance to AHSD-specific research covered self-care [120], mindfulness [32, 163], remote mediation [63], machine learning in mental health [165], designing for vulnerable population [156] and emotion regulation [152]. While these works contributed interesting insights into their discipline, they significantly helped us develop confidence in our own review scope.

Affective Computing Lens: Reviews catering towards affect perception and modelling include mental well-being technologies [193], affect recognition using EEG [1], sentiment analysis [114], body gesture [119], visual cues [126], social signal processing [179], stress detection using wearable sensors, bio-signals and activity data [18, 51, 53]. Although not haptics-specific, the research concepts and methods discussed in these reviews are applicable to various components of AHSD research such as emotion sensing, modelling, and analysis.

3 METHODS

In this scoping review, we addressed our research questions through analysis of "facets" chosen for their potential influence in shaping AHSD research, and spanning the researcher's background, theoretical and ethical grounding, type of research impact, and technological and evaluative approach and methods. These facets, detailed in (Figure 4), allowed us to draw a detailed picture of how research on AHSD has been conducted and has evolved in the past decade.

Our review methodology included five steps [3]: pilot review, database search, preliminary screening, secondary screening, and analysis. Figure 3 visualizes our process with venue-wise paper counts. Steps 1-4 were conducted by the lead author under the supervision of the last author; in Step 5 the team was expanded to include two additional collaborators (coders).

3.1 Generation of Screening Parameters and Draft Dimensions

In our pilot review, we conducted a cursory Google Scholar search for papers published in the range of years 2010–2021 using a combination of 'haptics' AND ('affective health' OR 'mental health' OR 'emotion regulation') as the search string. We explored papers using a snowballing process [192] and eventually selected 15 papers based on relevance. We then reviewed these papers to identify our search keywords (Table 1) and establish inclusion-exclusion criteria. This preliminary review also helped us inductively create the first draft of our list of *dimensions* and *values*, informed by our research questions (Figure 4).

For search keywords, we created two independent sets containing affect and haptic-related terms respectively, targetting relevant themes in these areas. We further split them into *Focus* keywords (that are specific to themes we observed in the pilot review) and *Generic* keywords (that attempt to capture a broader scope). In our scope, the technological nature of haptics research helps identify relevant literature using a specific set of technical keywords; however, the application-centric nature of affect research necessitates the use of a broader and more diverse keyword set to capture the breadth of affect-related methods and applications. Hence, the disparity in the size of the keyword sets.

Table 1: The 11 venues in our search set with their acronyms, venue size (2010-2021) reported as mean (m) and standard deviation (sd), and search keywords.

Human-Computer Interaction (published in ACM)	$K_{\text{Haptics+Affect}}$
Conf. Human Factors in Computing (CHI)	m: 536, sd: 157
Int. Conf. Tangible, Embedded and Embodied Interaction (TEI)	m: 46, sd: 10
Designing Interactive Systems (DIS)$^{\alpha}$	m: 105, sd: 23
Int. Conf. Multimodal Interaction (ICMI)	m: 55, sd: 12
Symp. User Interface Software and Technology (UIST)	m: 72, sd: 16
Trans. Computer-Human Interaction (TOCHI)*	m: 71, sd: 25
Haptics (published in IEEE)	K_{Affect}
World Haptics Conference (WHC)$^{\Phi}$	m: 107, sd: 14
Haptics Symposium (HAPTICS)$^{\alpha}$	m: 71, sd: 25
Trans. Haptics (TOH)*	m: 49, sd: 16
Affect (published in IEEE)	K_{Haptics}
Int. Conf. Affective Computing and Intelligent Interaction (ACII)$^{\Phi}$	m: 130, sd: 27
Trans. on Affective Computing (TAC)*	m: 46, sd: 37

Affect-related keywords (K_{Affect}):
Focus affect keywords to capture research corresponding to common mental health disorders [145] (*"depression", "anxiety", "bipolar"*) and common practises/therapies used for facilitating mental and affective health (*"mindfulness", "meditation", "breathing", "coping", "emotion communication", "CBT", "DBT"*); Generic affect keywords to capture research corresponding to mental and affective health (*"mental health", "affective health"*) and emotion regulation practises/therapies (*"emotion regulation", "affect regulation", "psychological intervention"*)

Haptic-related keywords (K_{Haptics}):
Focus haptic keywords to capture variety of technologies (*"vibrotactile", "force feedback", "kinesthetic", "tactile"*); Generic haptic keywords for extended scope (*"touch", "haptic"*); Additional keywords to capture papers not mentioning haptic-related terms but including such work (*"tangible interface", "wearable"*)

m=mean, sd=standard deviation *journal $^{\Phi}$odd-year $^{\alpha}$even-year

3.2 Database Search

For our main review, we selected 11 ACM and IEEE venues (Table 1) corresponding to research areas of Human-Computer Interaction (HCI), Haptics, and Affective Computing. Given their longevity, all these venues can be considered well-established. We chose venues that covered the entire time span of our scoping review in order to facilitate analyzing venue-wise yearly trends in the future, which meant excluding venues like IMWUT (a relatively newer HCI journal) as it only covers the late decade. Within HCI, we preferred to

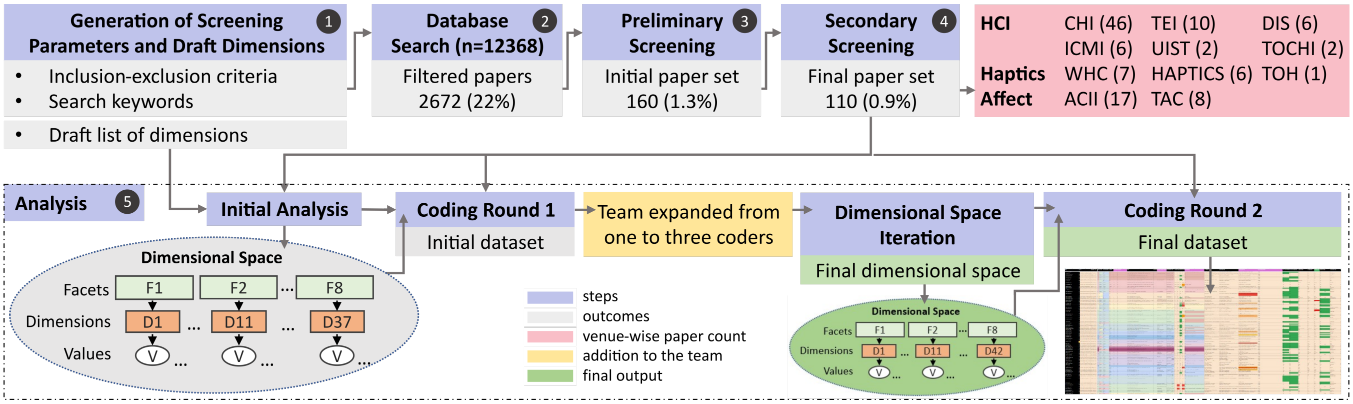

Figure 3: Review methodology shown as a modified Prisma Diagram [125]. The circled number on boxes' upper right corner refer to Sections 3.1–3.5 of this paper. Oval shapes represent our three-tier dimensional space, with its hierarchy of Ⓕ facets, Ⓓ dimensions, and *values*.

sample papers from venues which had a generalized scope, as there would be a low probability of finding AHSD work in an otherwise specialized HCI research area, for instance, PACM-HCI (CSCW) specifically covers technology to support collaborative work, and UbiComp primarily covers the development of ubiquitous interactive and computing systems, and thus were considered out of scope. We acknowledge missing possible relevant contributions through these exclusions, but given time and effort constraints, we chose to focus on in-depth searches in limited venues instead of peripheral broad searches, and address the same in our limitations.

We included publications from Jan 2010 until Jun 2021 (11.5 years, and a total of 12368 papers). We defined this period based on several criteria. An approximate 10-year span appeared both interesting and feasible based on known interesting developments and initial task assessment. Because of biannual venues, an even-numbered year span was critical. The terminus in 2021 was the date at which we commenced analysis. Because this was close to the natural decade boundary we advanced the start year to 2010. Given the publication timeline of venues, our paper set for 2021 only included papers from CHI and TEI as they were the only venues publishing before June. Throughout the paper, we refer loosely to this 11.5-year span as a *decade*.

To find papers that addressed the overlap of HCI-haptics-affect in AHSD research, we filtered papers that contained at least one keyword each from haptic and affect-related keyword lists (Table 1). For HCI venues we used a combination of the haptic and affect keywords, using the boolean operator AND, for haptic venues we only used affect-related keywords, and for affect venues, we only used haptic-related keywords. Based on these inclusion criteria, we ran a full-text search capturing publications that mention these keywords anywhere in the article to arrive at 2672 *filtered papers*.

3.3 Preliminary Screening

Post the database search, we conducted a preliminary screening of our filtered 2672 papers, excluding papers that (1) discussed purely software-based technologies, without any haptic components, *e.g.*, mobile self-tracking apps, (2) used "touch" as an input method, not for sensing affective states, *e.g.*, journal entry in smartphone apps through touch screen (3) used "affect" as a verb, *e.g.*, smoking affects lungs, or (4) studied, designed, and evaluated haptic affect technologies primarily for entertainment, recreation, and marketing. We carefully perused the publication title, keywords, and abstract, (in cases of ambiguity, we skimmed the full text) and excluded papers that were not relevant. This step yielded 160 papers as our *initial paper set*.

3.4 Secondary Screening

In our secondary screening, we briefly analyzed the full text of each of the 160 papers and tagged them with a relevance index (high, medium, low). This was done to help the lead author triage and prioritize highly relevant papers while analyzing. Papers tagged as 'low relevance' could have future applications in enhancing the user's affective state but in their current stage they primarily focussed on interaction and immersion, *e.g.*, affective wearable for creative design, emoti-chair for composing music. We dropped these papers for scoping purposes and got a *final paper set* of 110 papers.

3.5 Analysis

The lead author analyzed 74 out of 110 papers in the final paper set tagged as 'high relevance' and coded them using the list of *dimensions* drafted in Section 3.1. Through this initial analysis, the lead author (under supervision) iterated on the *dimensions*, eventually defining a set where every dimension was either *categorical* (having two or more fixed entries), *descriptive* (open-ended entries), or *metadata* (see Figure 4). They defined a set of *values* within each *categorical dimension*, then grouped all *dimensions* into *facets* (related to the research questions). This three-tier organization of *facets*, *dimensions*, and *values* (Figure 3) is henceforth referred to as our *dimensional space*. At this stage, the lead author deductively coded the rest of the papers using this space, generating our *initial dataset*.

To enhance the quality of coding and ensure consistency, two additional coders (also co-authors for this work) conducted the second

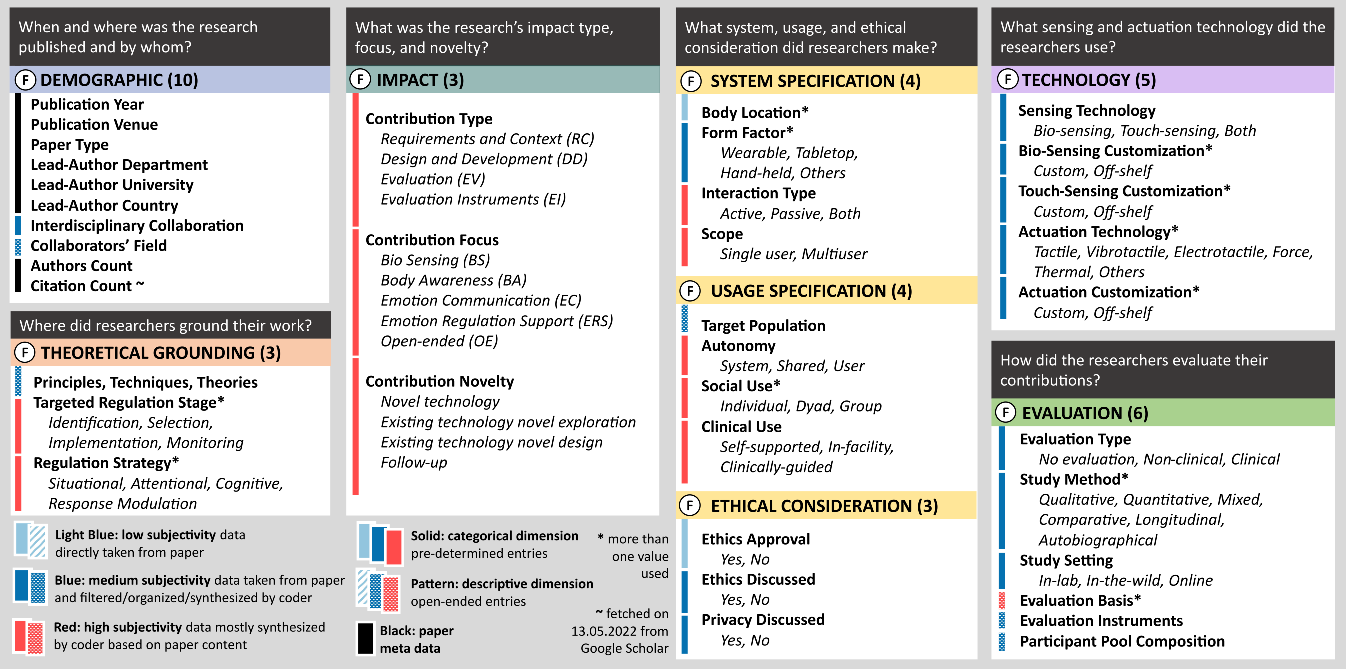

Figure 4: An overview of our dimensional space with 8 Ⓕ facets contextualized by our research questions in black boxes, 38 Ⓓ dimensions (bold-font text), and *values* (italics). The vertical colored bars on the left represent the type of dimensions and the subjectivity of its data coding (see legend). Ⓕ facets are organized as sub-sections in Section 4. Across this paper, we use the indicated acronyms for the *values* of the Ⓓ Contribution Type and Ⓓ Contribution Focus dimensions within the Ⓕ Impact facet.

round of coding, where the 110 papers in the final paper set were randomly split and assigned equally to each new coder. To ensure a reliable coding process between the three coders, we required a uniform understanding of the dimensional space. To that end, we (1) collectively reiterated the definitions of the *facets*, organization of *dimensions* within the *facets*, and the choice of *dimensions* and definitions of *values*; and (2) individually coded a common subset of 10 papers, post which we had a round of discussions to achieve a consistent understanding of the dimensional space. The average inter-rater agreement among the three coders for these 10 papers was 80%.

Based on our updated and uniform understanding of the dimensional space, the new coders coded the 110 papers while the lead author updated the initial dataset generated from the first coding round. In case of conflicts within categorical dimensions, the best-suited value was chosen through discussions among the coders, and for descriptive dimensions, data from both coders were merged. At the end of this second round, each paper was coded twice, to generate our *final dataset*, scaffolded by our *final dimensional space*. Our final dataset is open-sourced and can be accessed here: https://osf.io/kg2sm/

4 RESULTS

The eight facets of our dimensional space can be understood as different perspectives on the dataset answering our set of research questions. In the following, we present our analysis grouped by facets to first visualize the most interesting trends and comparisons revealed by the dimensions it contains, then unpacks the available insights in words. In some cases, our visualizations juxtapose two or more dimensions to expose how their values are distributed. In other cases, we look for trends within dimensions, either annualized or in 4-year clusters to find larger patterns from uneven data.

We normalized clusters by the number of papers published in that year range: *early* (2010–2013), *mid* (2014–2017), and *late* (2018–2021) decade. As some included venues publish biannually, we required an even-numbered range duration; for this dataset's density, 4-year clusters were the most insightful.

(Text-format note: From this point onwards, dimension names are formatted in **bold-fonts** and values in *italics*. Wherever necessary, dimensions are also marked with a tag Ⓓ and facets with Ⓕ for easy identification. If a **dimension** is coded with multiple *values*, we mark it with an *asterisk. Percentage data (%) mentioned in this section is out of 110 unless stated otherwise.)

4.1 Ⓕ Demographics: When and where was the research published? Who was involved?

We analyzed papers from January 2010 to June 2021 for the venues listed in Table 1. All of our selected venues publish annually except ACII, HAPTICS, and WHC (biennial); and DIS (biennial until 2015). Overall, our final paper set accounts for 0.9% of publications in these venues during the selected time frame.

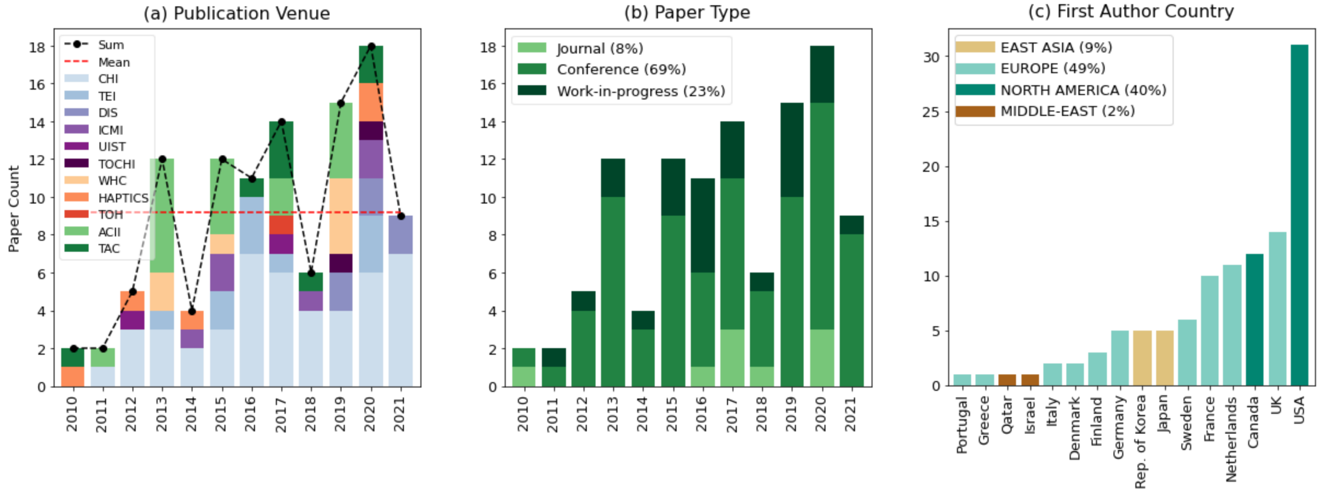

Figure 5: Overall count of papers by year, showing trends in Ⓓ dimensions (a) Publication Venue and (b) Paper Type across the decade, and (c) Country identified for lead author (colour-coded for the geographical region).

AHSD Visibility within Venue: For each venue, we calculated the ratio of papers appearing in our final set to the total published in the venue. ACII has the highest ratio (2.6%), followed by TEI (1.8%) and TAC (1.6%). Aside from the very large and broad CHI, the lowest is 0.18%. The highest ratios are for mid-sized venues; ACII and TAC already focus on affect. It appears that affect is not as visible within haptics venues as haptics is within affect.

Ⓓ Publication Venue (Figure 5a): The total AHSD paper count trends upwards over the decade. There is a dip in most even years, attributable to ACII's biennial (odd-year) format, with the exception of 2020. 44% of all AHSD papers we found came from the late decade. HCI venues lead the overall publication count (65%), followed by affect (23%), and haptic venues (13%).

Ⓓ Paper Type (Figure 5b): Contributions meeting our search criteria include *conference*, *work-in-progress*, and *journal* papers. Here, *conference* identifies full-length peer-reviewed papers (usually 6–12 pages) in conference venues, while *work-in-progress (WIP)* captures shorter and non-archival formats, *e.g.*, demos, extended abstract, student design challenge, late-breaking work, work-in-progress, and interactivity.

We included WIP contributions to capture AHSD research encompassing novel technology, design exploration, and creative applications which may or may not have resulted in full-length papers. To understand how *WIP* papers progressed, we did an extended search (Google Scholar, 11 July 2022) for possible follow-ups. We first identified publications that included any authors of the *WIP* or cited it, then excluded works with similar research themes but including a new design, device, or method. Based on such criteria, we found follow-up works for six *WIP* papers. In these papers, researchers followed-up on design [20, 141], device adaptability [45], and in-lab [76, 141] and longitudinal evaluation [158, 183].

Ⓓ Lead Author Country (Figure 5c), Department and University: All but 2 authors (Qatar, Israel) came from North America, Europe and East Asia (Republic of Korea and Japan). This shows that the AHSD research which we surveyed is western-centric (the first 5 countries, all in North America and Europe, dominate with 78 out of 110 papers), which potentially overlooks cultural and social norms around touch and emotions, individual preferences, styles of interactions, and long-term usage in other parts of the world.

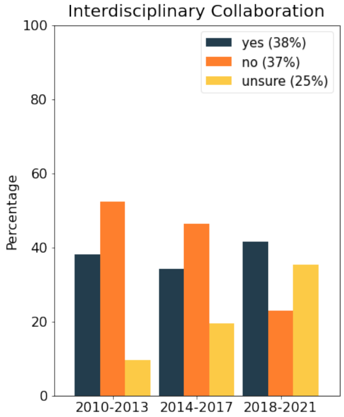

Figure 6: Trends in Ⓓ Interdisciplinary Collaboration, showing the % distribution of each *value* normalized by total papers in each 4-year cluster. In all graphs, % is the overall proportion of values over the decade.

For papers mentioning the lead author's affiliation as an academic Department (67%, n=74), 18% (20) comes from Computer Science. Other well-represented fields include Electrical and Computer Engineering (4), Industrial Design (5), and Information Technology (4). Universities publishing most often in AHSD (n>4) are the University of British Columbia (n=9), Stanford University (5), University of Twente (5), and Lancaster University (5).

Ⓓ Interdisciplinary Collaboration (Figure 6) and Collaborators' Field: Interdisciplinary collaborations have been widely shown to diversify perspectives and can lead to more thoughtful and inclusive design and decision-making [139]. We identified such collaboration based on authors' department affiliation (metadata or biographies): *'Yes'* required at least two authors from different disciplines. *'No'* meant the affiliated department of all authors are mentioned and all are the same, otherwise 'Unsure'. Journals are more consistent in including authors' bios; conferences' paper headers often only contain authors' organization. This metric itself is imperfect; even if this data were uniformly available, this approach would miss the disciplinary differences within academic departments, which themselves can be quite broad. However, such differences tend to be smaller than cross-departmental jumps, and our method is consistent across the decade, giving some reliability to relative values.

While interdisciplinary collaboration increased in the late decade, only 38% of selected papers involved interdisciplinary collaborators; 25% were tagged *'Unsure'*. Furthermore, the proportion of late-decade papers not reporting author discipline increased (48% of papers in 2020–21), with CHI especially uninformative (35% of papers from this venue). This reporting omission is unfortunate. Diverse backgrounds, culturally and academically, enrich research quality; individuals' backgrounds inform and bias it. If publication venues established standard protocols reporting researchers' departments, affiliations and backgrounds, it would provide a lens for interpreting methods and foci, and support meta-analysis.

We gathered the collaborator's department affiliations and found a skewed but diverse spread. The majority (47%) are from three groups (Computer Science, Industry, Engineering, where the Industry captures any collaborator mentioning a commercial affiliation); others (32%) represent Design, Interaction Technology, Psychology, Information Studies, Medicine, Neuroscience, Interdisciplinary Research, Art, Linguistics, Cognitive Science, and Statistics.

Ⓓ Author and Citation Count: We found a median author count of 4 (range 1–11). Citation Count (Google Scholar, 13 May 2022) shows 6 papers with over 100 citations [9, 75, 78, 123, 146, 159]. Schmidt *et al.*'s paper [146] presenting WESAD, a multi-modal dataset for stress and affect detection, leads the count with 287 citations; followed by Höök *et al.*'s work on 'Somaesthetic Appreciation Design' [78] with 211 citations. Citation distribution was skewed: 60% of the total citations of papers in this dataset were received by 22% of the papers (0–50 citations: 86 papers, 51–100: 18, 101–300: 6).

4.2 Ⓕ Theoretical Grounding: Where did the researcher's ground their work?

Given the wide scope of AHSD research, we need to know which theories, principles, and techniques prominent in affect and other fields are providing foundations for formulating hypotheses, design generation, discussion and analysis.

In our review set, 68 papers (62%) reported some form of theoretical underpinning, 34 (31%) of these in the last third of our review period. In the following, we unpack these underpinnings.

Ⓓ Principles, Techniques & Theories (Table 2) : Papers used *affect representations* to map emotions to a discrete multi-dimensional space, psychological *theories* to ground their methods, evidence-based *therapies* and popular emotion regulatory *practices* to formulate research and motivate their designs, and psychologically-grounded *affect and related models* to formalize their understanding of emotion and emotion regulation process (Table 2). Notable influencers in our dataset include Russell's Circumplex Model [142] (informed 16% of papers, n=18); Somaesthetic Appreciation Practise [78] (influenced eight subsequent papers); and Gross's Process Model [57] (formalized the stages of emotion generation and strategies of emotion regulation (ER)). Two dimensions — **targeted regulation stage** and **regulation strategy**) — in the theoretical grounding facet were inspired by Gross's Process Model to orient and clarify what part of the process a particular ER strategy is focused on and in what target stage it can be applied. Only three papers explicitly mentioned and applied Gross's model; for the rest, our coder team inferred the *values* based on the information provided in the papers.

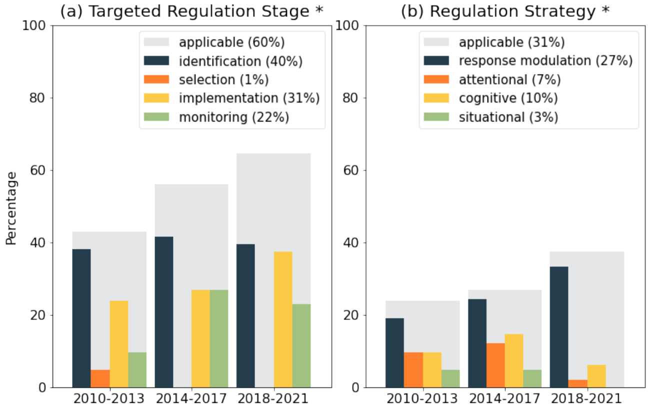

Figure 7: Trends in Ⓕ Theoretical Grounding. Coloured bars show the % distribution of each *value* normalized by total papers in each 4-year cluster for (a) Ⓓ Targeted Regulation Stage, (b) Ⓓ Regulation Strategy. Gray underlay shows % of papers for which the dimension was applicable, where applicable denotes the proportion of papers for which this dimension was applied. Asterisk* indicates multiple values could be applicable per paper.

Ⓓ Targeted Regulation Stage* (Figure 7a): We coded papers that target specific affect regulation stages (n=63) with four *values* from the Gross model: *identification*, *selection*, *implementation*, and *monitoring*. We did not tag papers that may eventually lead to such design outcomes in the future, claimed a *Requirements and Context (RC)* **contribution type**, or included open-ended design.

In all 4-year clusters, a consistent focus remained on *identification* (~40%), with noticeable increases in *monitoring* (mid and late decade) and *implementation* (late decade) – a presumed causal effect of increased **contribution focus** on *body awareness (BA)* and *emotion regulation support (ERS)* which benefits from affect stage *identification* and *monitoring*, and involves *implementation* of regulation strategy.

Table 2: Various Ⓓ Principles, Techniques, and Theories used by researchers, categorized, with citations

Theory [Citation]
Affect Representations: Russell's Circumplex [9, 15, 62, 65, 84, 96, 113, 128, 146, 147, 164, 169, 174, 176, 189–191, 195], Pleasure, Arousal and Dominance [49, 118, 169, 170, 180], Unipolar Valence [108, 110]
Theories: Ekman's Emotions [35, 46, 62, 65, 67, 84, 118, 122, 128, 147, 169, 173, 190, 191], Conceptual Act Theory of Emotions [59], Social Cognitive Theory [147]
Therapies: CBT (Cognitive Behaviour Therapy) [14, 77, 127], DBT (Dialectical Behaviour Therapy) [166], Pet Therapy [39, 82], AAT (Animal Assisted Therapy) [147], MBSR (Mindfulness-Based Stress Reduction) [30, 140], MBCT (Mindfulness-Based Cognitive Therapy) [140]
Practises: Somaesthetic Appreciation [30, 31, 47, 69, 78, 85, 144, 158, 162, 168, 174, 176], Guided Acupressure [127], Guided Breathing [6, 127, 180], Mindfulness [25, 30, 31, 45, 52, 77, 85, 115, 140, 141, 159, 166, 168, 175, 176], Feldenkreis [158], Grounding [30, 31, 45, 69, 78, 118, 140, 162]
Affect and Related Models: Fogg Behavior Model [199], Kübler-Ross Model [183], Gross's Process Model [108, 109, 111]

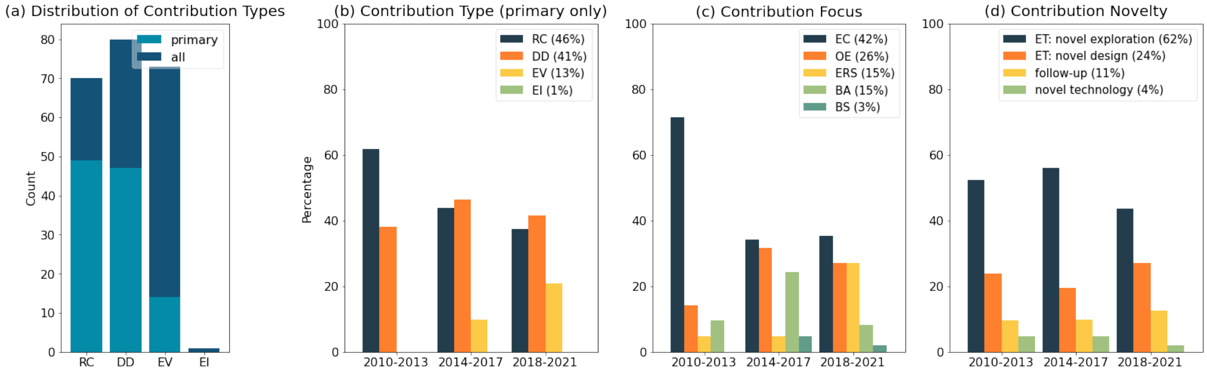

Figure 8: Trend in Ⓕ Impact over the years: (a) Paper count by Ⓓ Contribution Type. Light blue bars (primary) sum to the total papers in the data-set; dark blue appends papers with that type as non-primary. (b-d) Colored bars show the % distribution of each *value* normalized by total papers in each 4-year cluster for (b) Ⓓ Contribution Type (primary), (c) Ⓓ Contribution Focus, and (d) Ⓓ Contribution Novelty, where ET means Existing Technology.

Ⓓ Regulation Strategy* (Figure 2b): Papers having *implementation* as **targeted regulation stage** (n=34) were coded with four *values* from the Gross model: *situational*, *attentional*, *cognitive*, and *response modulation*, with multiple tagging as appropriate. We observed dominance of the *response modulation* strategy over the years with relatively less focus on the other three strategies. This might be due to the complex nature of implementing and evaluating such support using touch-based devices.

4.3 Ⓕ Impact Type: What was the research's impact type, focus and novelty?

Ⓓ Contribution Type (Figure 8a): We were interested in trends in research impact and type of contribution, hence, we coded papers with *values* including *Requirements and Context (RC)* (foundations informing design and methods), *Design and Development (DD)* (exploration and actualization of design and devices), *Evaluation (EV)* (assessment of such designs and devices), and *Evaluation Instruments (EI)* (development of AHSD-specific instruments). These categories are further expanded in Table 3. We tagged *all* values applicable to each paper's content and noted its *primary* contribution. Each paper appears once (in counts and figures) under its primary contribution designation.

The majority of papers include *RC*, *DD* and *EV* work, with *RC* and *DD* as most frequent primary contributions (Figure 8a, Table 3). No papers had a primary *EI* contribution. Figure 8b shows that *RC* papers were prominent in the early decade, *DD* balanced RC in the mid-decade and took over *RC* in the late decade, and *EV* increased over the course of the decade starting from null. This seems like a natural trend in any research field where requirement and context work is followed by design and development, and evaluation. Although evaluation-centric papers (*EV*) increased, we did not see corresponding AHSD-specific *evaluation instruments* (*EI*) in our paper set. We foresee the need for more standardized questionnaires, scales, and paradigms for evaluating haptic affective devices as the field matures.

Ⓓ Contribution Focus (Figure 8c): We found five research themes (*values* under **contribution type**) and coded papers based on their primary research focus: *Bio-Sensing (BS)* (sensing user's physiological and touch data), *Body Awareness (BA)* (facilitating user awareness of their physiological activity and affect, hence, one step further than bio-sensing), *Emotion Communication (EC)* (mediating affective communication between a system and a user or between two or more users), *Emotion Regulation Support (ERS)* (facilitating users' implementing emotion regulatory practises, *e.g.*, breathing, meditation, mindfulness, stress regulation), and *Open-Ended (OE)* (not mentioning any specific research focus).

Researchers have been inclined towards *emotion communication* (*EC*) topics throughout the decade. Contextualizing **contribution type** with **contribution focus** (Figure 9), we found that most *requirements and context (RC)* research is either open-ended or

Table 3: Ⓓ Contribution Type with sub-categories and citations, (% shows ratio of papers with that contribution type in our dataset, with n=corresponding number of papers).

Contribution Type	Sub-categories
Requirements and **C**ontext (46%, n=51)	**understanding touch:** perception study [9, 21, 49, 67, 96, 102, 118, 128, 148, 162, 173, 190, 191, 194], touch and affect [30, 46, 96, 113, 138, 148, 169, 172, 190, 191, 194, 195] **understanding user-context:** studying target user [183, 197], curating relevant dataset [146, 182] **building research infrastructure:** architecture [80, 111], framework [31, 35, 65, 182], pipeline [35], data collection protocol [48, 108, 186] research test-bed [109] **informing design:** guidelines [47, 69, 92, 118, 162], design exploration [8, 14, 15, 22, 23, 31, 54, 64, 77, 78, 82, 85, 92, 118, 122, 127, 143, 155, 164, 166–168, 176, 184, 196, 198], design space [31], and design recommendations [30, 37, 39, 65, 107, 123, 128, 176, 183, 189] **summarizing past research:** survey [64, 74]
Design and **D**evelopment (41%, n=45)	**design** [15, 22, 42, 47, 54, 59, 77, 78, 80, 92, 107, 122, 127, 158, 166–168, 183], **technology** [115, 118, 130, 159], **device** [8, 14, 19, 20, 22, 23, 25, 31, 34, 38, 41, 42, 44, 45, 47, 54, 58, 59, 65, 69, 76, 76, 78, 85, 87, 92, 93, 108, 115, 118, 121, 129, 130, 140, 141, 150, 155, 157, 168, 170, 176, 184, 189, 194, 196, 197, 200], **method** [6, 7, 21, 25, 34, 36, 39, 47, 50, 52, 62, 65, 84, 96, 121, 123, 140, 147, 150, 159, 164, 170, 173, 180, 187, 190, 191, 195–197, 199], **development** [42, 47, 50, 59, 62, 65, 78, 80, 92, 108, 194], **toolkit** [36, 52, 174], **research tool** [134, 149]
Evaluation (13%, n=14)	**design** [15, 59, 80, 107, 122, 167], **device** [8, 14, 19, 22, 25, 31, 41, 44, 45, 54, 58, 69, 76, 78, 82, 87, 92, 93, 108, 110, 113, 115, 118, 130, 140, 155, 176, 189, 194, 200], **method** [6, 21, 23, 25, 34, 39, 42, 47, 49, 50, 52, 62, 65, 82, 84, 92, 96, 110, 121, 123, 128, 129, 140, 144, 147, 159, 164, 170, 172, 173, 175, 180, 184, 190, 191, 195, 197–199], **toolkit** [36, 174], **research tool** [149]
Eval. **I**nstruments (1%, n=1)	**rating scale** [148]

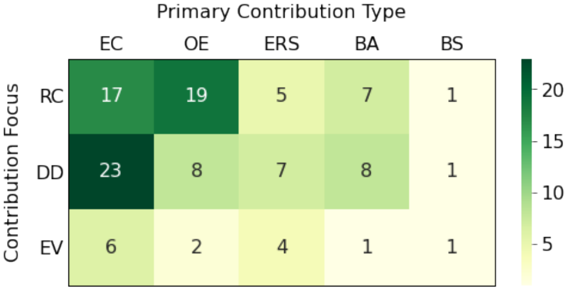

Figure 9: Contribution distribution based on primary Ⓓ Contribution Type and Ⓓ Contribution Focus, by paper count.

supports *EC* work, and most *design and development (DD)* research is also skewed towards *EC*. Although *EC* research is prominent overall, *BA* and *OE* works increase mid-decade (Figure 8c). We attribute the rise of *BA* work to the AHSD research inspired by practices like somaesthetics and mindfulness. We also see a late-decade rise of *ERS* work (56% of such papers in 2020-21), possibly attributable to the emotional distress caused by the COVID-19 pandemic [86] or influence of emotion regulation research in psychology [28]. As a general trend, there is a promising diversification in contribution focus over time (Figure 8c).

Ⓓ Contribution Novelty (Figure 8d): To understand novelty evolution, we coded papers based on *values* of *existing technology: novel exploration* (either use existing technology for a new use-case with no considerable change in design or do grounding work for applications of existing technology), *existing technology: novel design* (use existing technology with substantial design and development work), *follow-up* (present a continuation of authors' published work), and *novel technology* (presents new technology for haptic sensing and actuation in a AHSD context). Figure 8d's timeline shows that relative **contribution novelty** holds steady throughout the decade: most frequent are papers about *existing technology: novel exploration*, followed by *existing technology: novel design* then *follow-up* and *novel technology*. This consistent bias towards novel exploration with existing technology might be due to either or both the resource-intensive nature of developing new technology and the possibility of re-purposing generic technology developed for another purpose. We also see a low count of *novel technologies*. Possibly, research papers encompassing such technologies do not always correspond to a certain AHSD application or propose one. Such papers may be relatively open-ended, and/or appear in venues outside of our review's scope.

4.4 Ⓕ System Specifications: What design aspects did researchers consider when conceptualizing their AHSD systems?

Conceptualizing an AHSD design requires many decisions, including the type of interaction and how that exchange will support personal and shared needs, where it will be placed or worn, and how it will look. This facet focuses on specifications including body location, form factor, interaction type, and scope. We use "system" broadly to encompass design, device, technology, method or integrated system.

Ⓓ Body Location* (Figure 10a): Papers varied in the locus of haptic perception or point of physical contact. *Hand*, *arm*, or *wrist* unsurprisingly appeared most (74%, n=81), considering social acceptability for wearable devices (*e.g.*, smartwatch, fitness bands), high tactile sensitivity, and practicality. However, body location diversifies over time.

Ⓓ Form Factor* (Figure 10b): Most research focused on *wearables*: sleeves [93, 121, 200], wristbands [14, 25, 58], jackets [34, 45, 115], drapes [134], footwears [173], necklaces [31], scarfs [189], and pendants [47]. Moreover, relative wearable numbers grew over time, following the dominance of *hand/arm/wrist* **body location**. This trend is likely supported by improvements in compact, low-power and wireless technology: more precise and compact sensors and actuators, high-capacity micro-controllers and other maker electronics, and wireless Bluetooth and WiFi modules [95].

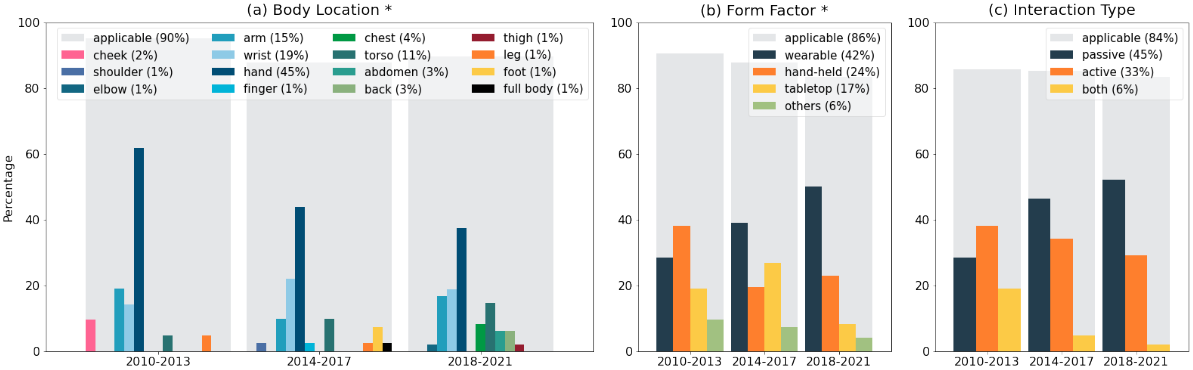

Figure 10: Trends in Ⓕ System Specification. Coloured bars show the % distribution of each *value* normalized by total papers in each 4-year cluster for (a) Ⓓ Body Location, (b) Ⓓ Form Factor and (c) Ⓓ Interaction Type. Gray underlay shows % of papers for which the dimension was applicable.

Tabletop (17%, n=19) and *hand-held* (25%, 27) formats were also popular. *Tabletop* devices were mounted on a fixed surface and *hand-helds* movable, but neither were worn. These devices often evoke day-to-day objects or artifacts, such as a flower vase [183] or cushion [122]. Some are activity-oriented (steering wheel or car seat [6, 7] for in-driving stress regulation; a mouse [159] for stress measurement during desk work), chosen for integration into daily life and more ubiquitous interaction.

Ⓓ Interaction Type (Figure 10c): Papers contributing a design or device can consider *active*, intentional and usually manual engagement, *e.g.*, touch-initiated interaction with robotic sheep [39]; or an experience that is *passive* from the user's perspective, initiated by the device and often operating in their attentional background – *e.g.*, passively conveying emotional information through multi-moji [190] or sharing bio-feedback [47]. We observed *passive* interaction increase over the decade.

Comparing dimensions, we found 10 out of 16 (62%) of papers with an *Emotion Regulation Support* **contribution focus** (Impact Facet) included *passive* interaction; 8 used a *Response Modulation* **regulation strategy** (Theoretical Grounding Facet); the others did not mention regulation. In general, there seems an increasing interest in technology running in the background and using physiological sensing to produce guidance, *e.g.*, regulated breathing [6, 47, 85, 158], mindfulness [140, 166], and meditation [45].

Ⓓ Scope: For design and device contributions, we approached this dimension through use scenarios and coded it with *values* of *single user* (62%, n=68) or *multiuser* (18%, n=20) interaction. We coded all wearable form-factors as *single user* scope, as well as some hand-held or table-top devices, *e.g.*, MouStress [159], Furfur [23], Azalea [69]. We coded devices like Robotic Sheep [39], Silka [155], CuddleBit [20] which can or will have interaction with more than one person in real-life deployment, as *multiuser*. The prevalence of *single user* scope is understandable as the obvious place to start in an emerging field, but given the under-studied state of shared access, shared use, or concurrent use of affective haptic devices (*e.g.*, among family members, friends, or community at home, office, or other non-private settings), we hope to see future research in *multiuser* interactions as the field advances.

4.5 Ⓕ Usage Specifications: In what kinds of use-cases were designs anchored?

Given its nature and novel stage, AHSD design is certainly a candidate for user-centred design. We analyzed how researchers anchored their designs or studies in specific populations, and considered spectrums of autonomy and eventual social or clinical use.

Ⓓ Target Population (Figure 11a): A majority of papers did not mention specific target groups and this proportion held steady over the decade; however, we do see great examples of user-specific design (Table 4). Given the modest prevalence, we argue for more research involving specific target populations having diverse needs to foster inclusivity. Especially, for cases where such designs are developed for minorities coming from different socio-cultural backgrounds, and clinical or young populations that may have unique cognitive or physical needs.

Table 4: Types of Ⓓ Target Population categorized based on Relationship/Medical Condition/Activity/Researchers, with citations.

Relationship: father-child dyad [107], long-distance couples [23, 44, 54, 69, 87, 129, 130, 167], long-distance family members [44, 54, 87, 130, 155, 167], closely related adults [65, 102, 122, 138, 197], palliative patient and their loved ones [183]

Medical: people in addiction recovery [77], people with dual diagnosis of a learning disability and borderline personality disorder [166], dementia patient [39], pediatric patient [82],

Activity: meditation practitioner [31, 45], public speaker [14], driver [6, 7], computer user [159]

Researchers: people conducting research in AHSD [35, 46, 52, 64, 74, 78, 96, 111, 121, 128, 146, 148, 149, 169, 182, 186]

Ⓓ Autonomy (Figure 11b): In design and device papers, how often does device control lie with the *system* or the *user*, *vs.* being *shared* between them? Here, assigning control to the *user* typically

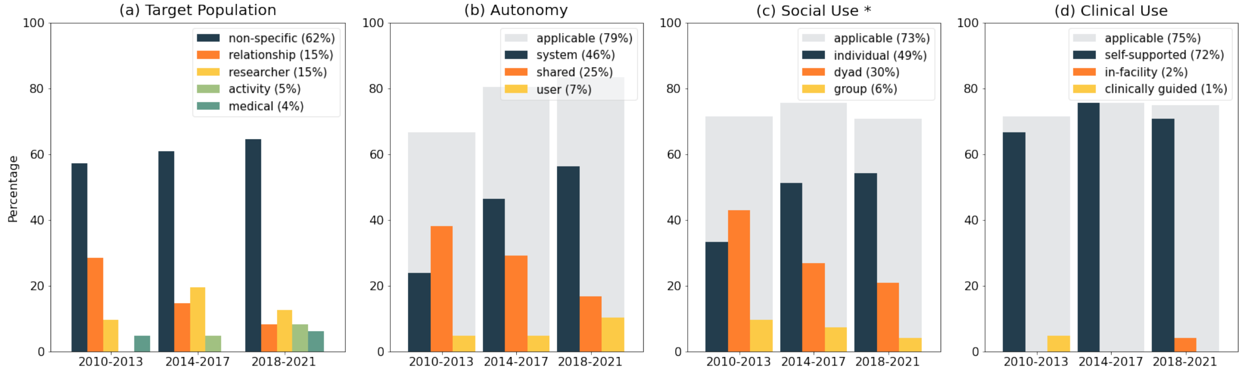

Figure 11: Trends in Ⓕ Usage Specification. Coloured bars show the % distribution of each *value* normalized by total papers in each 4-year cluster for (a) Ⓓ Target Population, (b) Ⓓ Autonomy, (c) Ⓓ Social Use, and (d) Ⓓ Clinical Use. Gray underlay shows % of papers for which the dimension was applicable.

means considering their preference in designing, selecting, or altering interaction; setting or altering goals; or any other form of decision-making. *Systems* gained autonomy over time, with *shared* initially prominent and then decreasing in the mid and late decade. However, while technological advances have ensured *systems* can operate with decreased *user* input, that does not justify removing or limiting *user* autonomy in AHSD designs. This seems to be a general opinion as well, as we see a gradual uptake in *user* autonomy in the late decade.

Ⓓ Social Use* (Figure 11c): We found social contexts for designs associated with specific use cases of *individual vs. dyad vs. group* mediation, tagging papers with multiple categories in some cases. *Dyad* use was initially prominent, likely due to couples-communication being a popular early use case, but *individual* use surpassed it by mid-decade. *Group* use was low throughout, under 10% in each 4-year period.

Ⓓ Clinical Use (Figure 11d): Papers with specific use-cases described AHSD systems intended to be *self-supported* (personal use and self-help), *clinically-guided* (personal use with help of clinical experts, *e.g.*, therapists, doctors, nurses) or used *in-facility* (personal or shared use in a medical facility). A majority (72%, n=79; steady over time) proposed *self-supported* use, with just two *in-facility* [39, 82] and one *clinically-guided* [166]. This is unsurprising given the challenges and burden of conducting HCI research in clinical settings, but unfortunate given the need for clinical validation of system effectiveness.

4.6 Ⓕ Ethics: What ethical and privacy issues did researchers consider?

27 papers in our dataset reported some form of **ethics approval** for conducting their research; 67% of these were in the late decade. Independent of institutional ethics approval (for which, by the early decade, reporting was standardizing as a requirement), we looked for 'discussion' within papers. 22 papers discussed data privacy and 12 ethics; just 4 discussed both. Figure 12 shows a small growth in the number of papers discussing ethics and data privacy, with 50% of these in the late decade. While hopeful, the still-paltry closing percentage signifies minimal attention to ethical and privacy implications in AHSD research.

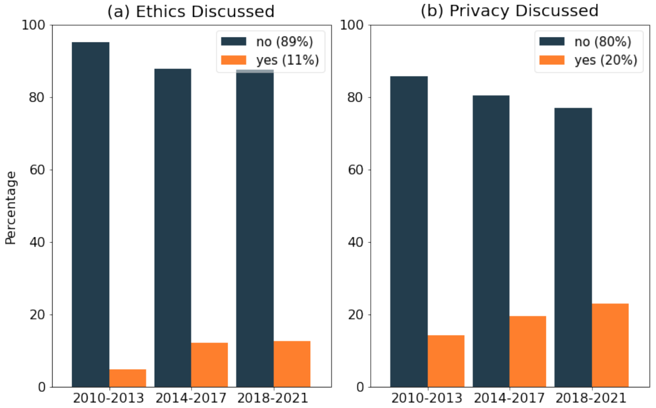

Figure 12: Trends in Ⓕ Ethical Consideration. Coloured bars show the % distribution of each *value* normalized by total papers in each 4-year cluster for (a) Ⓓ Ethics Discussed, and (b) Ⓓ Privacy Discussed.

Ⓓ Ethics discussed (Figure 12a): Of the 12 identified papers, 4 [39, 140, 144, 176] included a detailed discussion about ethics, and the rest a brief mention. We saw discussions in several different areas, and report it with enough detail to elevate positive examples.

Training and brainstorming – Thieme *et al.* [166] conducted pre-research training and brainstormed initial design concepts and safety, research governance, and ethical concerns with psychologists, nurses, and clinical managers to familiarize stakeholders with the research methods and implementation, and the risks involved.

Research methods – Chien *et al.* [23] used autobiographical research design to study the impact of their design by including user experiences from everyday life. Cabibihan *et al.* [19] addressed ethical constraints by using movie clips for emotional elicitation, exposing participants to potential real-life scenarios. Hutton *et* *al.* [77] respected the privacy of their target population while studying them in the context of AA and NA meetings and did not conduct research observations for 'closed' or members-only sessions. Gaffary *et al.* [50] explained the real objective of the experiment to the participants while conducting their study, and discussed the ethical context of their experiment with participants while conducting their study.

Design Conceptualization – Roo *et al.* [140] and Hassib *et al.* [65] discussed the goal of promoting autonomy during their design conceptualization. Neidlinger *et al.* [115] mentioned the eventual impact of their technology on ethical-decision making.

Research Reporting and Discussion – Daude *et al.* [30] and Umair *et al.* [176] reported ethical concerns voiced by participants during their study and included their verbatim responses. Feng *et al.* [39] and Sanches *et al.* [144] discussed the ethical challenges and implications of their work in detail.

Ⓓ Privacy discussed (Figure 12b): Of 22 identified papers, 5 [47, 64, 65, 130, 176] discussed privacy concerns and considerations in detail, with brief mentions by the remainder.

General Concerns around Data Privacy – Considering the intrusive nature of audio and visual logging [62, 130, 146, 183] some suggested tracking affect-related data via touch-interaction [62] and mouse-movements [159] to reduce privacy risks, and described the need for inconspicuous channels for sharing or displaying affect-related information to users [108]. Haptics was deemed an unobtrusive channel for communication while preserving user's privacy [36, 121, 175].

Design Conceptualization – Researchers included interactions to communicate the need for privacy [183], presented privacy options [36], designed form-factors like wristwatches with haptic or occluded visual display for discretion [14], chose enclosed spaces for private interaction [78], created personal artifacts with private data logging [166], reflected on privacy implications of design [47, 155, 180], and planned to support privacy needs in future designs [107, 130].

During the Study – Daude *et al.* [31] mentioned respecting participants' privacy during study set-up, allowing them to place required actuators themselves.

Reporting of Participants' Privacy Feedback – Some researchers also quoted privacy-centred remarks from users on the preference of sharing physiological data [176], platform design for affective communication [130], concerns about data storage and future malicious applications of such technology [30, 189], and nuanced data sharing dynamics (*i.e.*, selectively sharing positive emotions publicly but sharing negative states through private communication channels) [64, 65].

4.7 Ⓕ Technology: What sensing and actuation technology was used?

Haptics and affect involve both perception and display of touch from a user perspective – here, we discuss both the sensing and actuation technologies in our dataset, further organized in Tables 5 and 6.

Ⓓ Sensing Technology and Customization* (Table 5, Figure 13a): Papers that mentioned any form of physiological or touch-based sensing were tagged with *values* of *bio-sensing* and *touch-sensing* and likewise organized based on physiological (*i.e.*, heart rate, skin conductance, …) and touch data type (*i.e.*, two-state: sensing the occurrence of touch; variable: sensing the variability of touch in terms of location, pressure, bend, movement, and their combination; gesture: sensing meta-level touch sequences; and others: sensing touch using visual or neural data). Where specified, we observed high popularity of *off-shelf* (n=36) technologies over *custom* (8) for bio-sensing, whereas a somewhat balanced proportion of *off-shelf* (19) and *custom* (14) technologies for touch-sensing.

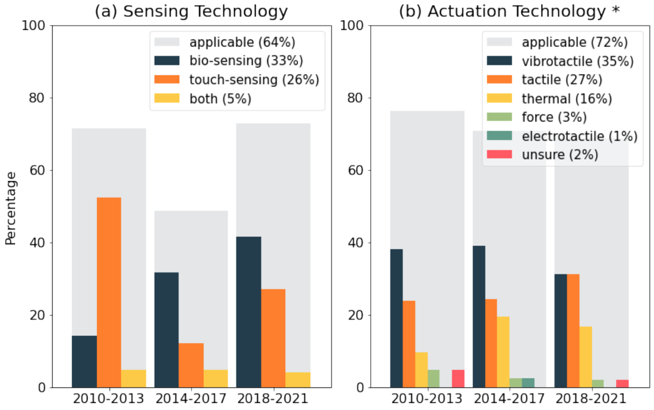

Figure 13: Trends in Ⓕ Technology. Coloured bars show the % distribution of each *value* normalized by total papers in each 4-year cluster for (a) Ⓓ Sensing Technology, and (b) Ⓓ Actuation Technology. Gray underlay shows % of papers for which the dimension was applicable.

We observe a progressive trend in *bio-sensing*, with the highest proportion in the last decade, attributed to recent technological advancements, particularly accessible *off-the-shelf* modules and progress in physiological data processing and sense-making [70]. *Touch-sensing* was popular in the early decade, dropped and rose again in the late decade but this time only for low-fidelity sensing *e.g.*, single location touch, single location-variable pressure, or visual or accelerometer-based tracking of touch gestures. Although these methods serve the purpose of *touch-sensing* relevant to these papers, we presume AHSD research can largely benefit from logging and sense-making of rich tactile information – which might involve sensing multi-location touch, pressure variability, shear, and other nuanced combinations of such parameters via a flexible, conformable, and durable form factor. In our dataset, we attribute the wave-like trend and relatively less popularity of *touch-sensing* to the unavailability of preferred *off-shelf* touch-sensors, and challenges involved in building custom sensors suiting research-specific needs. Although we do observe rapid advancements in *touch-sensing* technology in the fields of physics [116], engineering [91] and robotics [151], it is not reflected within Haptics, HCI and Affect venues, possibly due to siloing.

Ⓓ Actuation Technology* and Customization* (Table 6, Figure 13b): Papers including any form of haptic output were coded with *values* of *vibrotactile*, *tactile*, *thermal*, *force*, *electrotactile*, and

Table 5: Ⓓ Sensing technologies used, categorized as either Bio-sensing or Touch-sensing, showing the type of data sensed and technology/hardware used to sense it, with citations.

Data Type	Sensing Technology
	BIO-SENSING
Heart Rate (21)	**ECG:** Zephyr BioModule [6, 7, 109], Berkeley Tricorder [127], Florida Research Instruments TDE-201 Ag-AgCl [52], RespiBAN Professional [146], BIOPAC Inc. ECG100C Electrocardiogram Amplifier [113], non-specified [159, 182, 186] **PPG:** MioFuse [140], Mindmedia NeXus-10 [196], Pulse Sensor [25, 38, 108, 110, 115], Empatica E4 [146], non-specified [92] **Others:** chest strap [115], digital stethoscope [107], custom metal disk indents [166], YAGAMI Inc. microphone embedded stethoscope HBS-NA [198], non-specified [155]
Skin Conductance (19)	Empatica E4 [6, 7, 59, 122, 146], Thought Technology [108], Affectiva Q Sensor [109, 172], RespiBAN Professional [146], Philips DTI-2 wristband [144], Berkeley Tricoder [127], Bitalino bio-sensing Board [115], non-specified [52, 77, 110, 155, 174, 176, 182, 186]
Breathing (15)	**breathing strap:** Zephyr Biomodule [7, 109], Thought Technology [108], PLUX RIP Sensor [85], custom stretch bands [45, 52, 87, 107, 115, 140, 168], non-specified [141, 186] **others:** Sparkfun MPU-9250 9DOF IMU [47], distance sensor [158], EMG sensor [168], custom shape-changing pillow [168], non-specified [78, 110]
Respiration (2)	Analog Hall sensor [92], RespiBAN Professional [146]
Brain Activity (5)	**EEG:** MUSE [31], Emotiv EPOC2 [65], non-specified [52, 141, 182]
Eye-blinks (1)	**EOG:** non-specified [52]
Skin Temperature (4)	Empatica E4 [122, 146], RespiBAN Professional [146], Texas Instruments LM35 [46], non-specified [108]
Muscle Myoelectric Activity (2)	EMG-based: RespiBAN Professional [146], non-specified [186]
Gastric Myoelectric Activity (1)	OpenBCI Bioamplifier [180]
	TOUCH SENSING
Two-state (n=5)	**touch:** custom conductive thread [183], proximity switch [54], capacitive touch sensor [44] **squeeze:** custom sensor [44] **hug:** custom sensor [122]
Variable (n=24)	**touch:** custom conductive fur [41, 42] **location:** custom 15 -channel capacitive touch pad [75] **bend:** Spectra Symbol FS-L-0112-103-ST Flex sensors [19] **pressure:** FlexiForce SEN-08713 [50, 184], Interlink Electronics FSR 400 series [19, 138], load sensor [22], custom circular capacitive force-sensitive resistors [150], custom pneumatic compressables [36], custom soft-silicon button [130], custom capacitive sensor [200], non-specified [23, 167] **location + pressure:** custom piezoresistive fabric pressure sensor [41], custom lycra pads filled with conductive wool (Bekeart Bekinox w12/18) [75, 76], custom sensor made from EeonTex Zebra and SLPA 20 kilo ohm fabric and mesh separator [20, 21] **inertial movement:** Geomagic Touch X device [48], smart phone accelerometer [69, 197], ADXL335 3-axis accelerometer [92], mouse movement [159], non-specified accelerometer [44, 166]
Gesture (n=4)	**touch patterns:** TECHTILE haptic recorder [84], touch-screen [62, 129], touch sensors on off-shelf Pleo Robot [39]
Others (n=3)	**visible touch interaction:** LEAP (infrared camera) [67], Go Pro [82], Trackstar (electromagnetic tracking) [66] **neural effects of touch:** Logiq ultrasound and FHC recording electrode (microneurography) [67]

others. We observed a spectrum of *off-shelf* (n=36) as well as *custom* (n=31) technologies (Table 6), with the dominance of *vibrotactile* in the early and mid-decade (attributed to ease of use and seamless integration in wearables) matched by *tactile* actuation in the late decade, increasing popularity of *thermal* in the mid and late decade, and overall, scarce use of *force* and *electro-tactile*. Relatively unconventional technologies such as shape memory alloy [45, 58, 107, 176], ultrasound [123], piezo [143], and electrical-muscle simulation [65] marked their sporadic presence (Figure 1).

We noticed that 15% of papers (n=17) did not report the specifications of the haptic device. We encourage researchers to report such data for easily reproducible research. Few papers used a combination of multiple haptic actuation technologies [19, 189, 190] – a potential untapped opportunity as each technology becomes better understood in this context. We advocate for diversifying actuation technologies, customizing to account for context, *e.g.*, substitutes for noisy or visible actuation for use in public settings, or low-power options for wearables.

4.8 Ⓕ Evaluation: How did researchers evaluate their contribution?

We surveyed whether the evaluation was conducted, the methods and instruments used and the contexts examined. Metrics and studied populations expose what researchers target evaluating.

Ⓓ Evaluation Type (Figure 14a): 30% of papers did not report any sort of evaluation, while 70% of papers reported some kind of evaluation: 69% *non-clinical*, and a single *clinical evaluation* [82]. Over time, this imbalance holds but there is a slight increase in *non-clinical* evaluations conducted.

We did not formally include in our scope any venues which typically publish clinical evaluations, as we expected minimal occurrence. To inform this decision, we conducted a full-text search in PubMed for 2010–2021 using the superset of our keywords, selecting 'Clinical Trial' AND 'Randomized Control Trial' as the article type. We found several papers on clinical evaluation of touch-based practices like yoga, massage therapy, and reiki, but just one that evaluated a touch-based technology [160]. This seems to confirm that there have been few clinical trials of AHSD and that leaving

Table 6: Type of Ⓓ Actuation Technologies categorized based on targeted sensory receptor.

Actuation Type	Actuation Technology
Vibrotactile (n=39)	**ERM:** KOTL C1226A001F [75, 76], non-specified [109, 128] **LRA:** C2 tactors [108, 110, 149], Polulu Corp Shaftless Vibration Motor [19], Matsushita Electric Industrial Co. LVM8 [138], non-specified [7, 59] **piezo:** Nokia 770 Internet Tablet [143] **voice-coil:** Tactile Labs Haptuator [46, 96, 173, 190, 195], Tectonic Elements TEAX19C01-8 [121], Acouve Lab VP408 [198] **others:** Doppel wrist-watch [175]; Vivitouch electroactive polymer (EAP) [148], TECHTILE toolkit [84], phone/device haptic engine [80], custom AudioTactile fabric [115], custom electromagnetic soft actuator [25] **non-specified:** [14, 47, 77, 82, 107, 122, 127, 129, 130, 166, 176, 187, 189, 196]
Tactile (n=30)	**motor:** Futaba S3114 micro-servo [8], Tower Pro MG92B and SG92R servo [118], Dynamixel, AX-12A servo [50], non-specified servo motors [15, 20, 22, 147], Faulhaber 1624E0175 DC motor [121], DC motor [19], custom squeeze arm band [113, 184], **pneumatics:** non-specified [130, 168], custom air-jet system [169, 170], custom inflatables [9, 36, 85, 93, 115, 194, 197], custom air pump solenoid valve [87], custom Fluidic Fabric Muscle Sheets (FFMS) [200] **shape memory alloy:** [45, 58, 107, 176] **ultrasound:** [123] **others:** fidget spinner [92], physical embeddings [199]
Thermal (n=18)	**custom metal coil:** Cr20Ni80 Nichrome wire [197], Nickel Titanium SMA [45], 40-gauge wire [189], conductive fiber [176] **peltier:** [31, 34, 54, 134, 164, 174, 190, 191, 195] **others:** custom air and water based system [93], Embr Wave wrist-watch [175], Polyimide Heaters HK5200R5.2L12B [19] **non-specified:** [155, 158]
Force (n=3)	**grounded force-feedback device:** Geomagic Touch X device [48–50]
Electrotactile (n=1)	**electrical muscle simulation:** Breuer Sanitas SEM 43 [65]
Unsure (n=2)	Pleo Robot [39], non-specified [167]

clinical venues out of our search scope would not greatly impact our results.

Ⓓ Study Method***:** We tagged papers reporting a user study (n=90) with one or more values of *quantitative* (n=39), *qualitative* (18), *mixed* (33), *comparative* (5) and *longitudinal* (5). Out of the few evaluating AHSD systems over time [23, 39, 129, 144, 199], we highlight Chien *et al.*'s unique autobiographical study with its compelling insights into day-to-day integration and evolution of a emotion communication technology for *dyads*.

Ⓓ Study Setting: Although several researchers noted the need for *in-the-wild* evaluation (natural interactions in a familiar environment), few managed it (10%, n=11; *vs.* 71%, n=78 *in-lab* studies; n=1 *online*).

Ⓓ Evaluation Basis* **(Figure 14b):** We tagged papers reporting some form of evaluation with values of participants' subjective *preference* of design and its usability, *perception* of tactile stimuli and conveyed emotions, *usage* patterns; and of system *performance* and observed *impact*, marking multiple values as appropriate. Evaluation metrics centered on *preference* (41%), *performance* (29%), and *perception* (25%); only a few considered *usage* (12%) and *impact* (9%). *Preference* was most popular throughout the decade, followed by *performance, perception, usage,* and *impact.* In the late decade, we see relative increases for the last four. We argue for more evaluation based on long-term *usage* and *impact* in the future to achieve a nuanced understanding of the effectiveness of such devices in real-world settings.

Ⓓ Evaluation Instruments (Table 7): Researchers employed a wide selection of questionnaires, standard surveys and scales to serve their evaluation goals, often a mix of questionnaires from psychology, affect, and usability research. We foresee the need for standardized evaluation instruments tailored specifically for AHSD research.

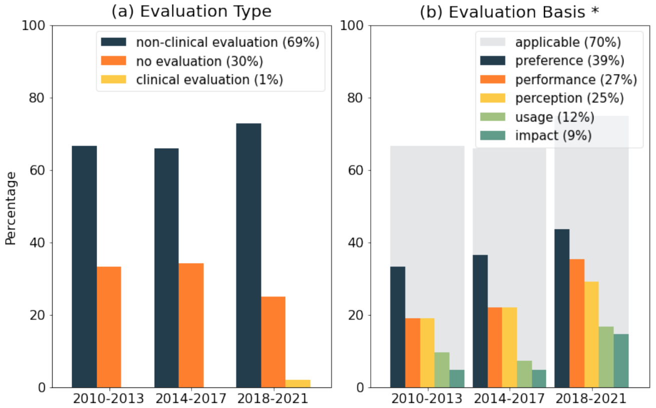

Figure 14: Trends in Ⓕ Evaluation. Coloured bars show the % distribution of each *value* normalized by total papers in each 4-year cluster for (a) Ⓓ Evaluation Type, and (b) Ⓓ Evaluation Basis. Gray underlay shows % of papers for which the dimension was applicable.

Ⓓ Participant Pool Composition

Gender and Age – Out of 2,038 participants reported in these papers, 53% (n=1065) were *male*, 46.9% (n=965) *female*, 5 *non-binary*, and 3 *non-disclosed*. 70% of the papers (77) reported gender-specific details of the participants involved in user studies. Some papers exclusively included *male* [50] or *female* [198] participants to avoid the effects of gender on results. Haptic emotion communication studied in the context of romantic relationships often included straight couples [66, 87, 102, 138], but none incorporated gender-diverse couples. Paredes *et al.* highlights the observed gender bias and hence the importance of tailoring haptic affective expression to different genders [128]. We did not analyze age as papers mentioned it sparingly and inconsistently – *e.g.*, a mix of mean, range or median.

Table 7: Ⓓ Evaluation Instruments, organized by purpose (derived from thematic analysis).

Evaluation Instruments
Affect
SAM [73] *Self-Assessment Manikin* [47, 65, 113, 118, 123, 146, 147, 164, 180]
PANAS [185] *Positive and Negative Affect Schedule* [15, 82, 184]
MMSE [43] *Mini Mental State Examination* [39]
OERS [177] *Observed Emotion Rating Scale* [39]
PAD [104] *Pleasure, Arousal and Dominance* [49]
BMIS [99] *Brief Mood Introspection Scale* [46]
NPRS [100] *Numeric Pain Rating Scale* [82]
FPS-R [72] *Faces Pain Scale Revised* [82]
FAS [117] *Facial Affective Scale* [82]
Custom Valence-Arousal Likert Scale [128]
Personality and Experience
BFMS [133] *Big Five Marker Scales* [182]
BFI [83] *Big Five Inventory* [110]
IOS [4] *Inclusion of Other in the Self* [122]
BSQ [29] *Body Shape Questionnaire* [110]
LEQ [13] *Life Events Questionnaire* [127]
Stress and Anxiety
STAI [153] *State-Trait Anxiety Inventory* [45, 82, 110, 127, 140, 146, 147, 175, 198]
SSSQ [68] *Short Stress State Questionnaire* [146]
SSR [10] *Subjective Stress Rating* [159]
PSS [26] *Perceived Stress Scale* [6, 7]
TAI [2] *Test Anxiety Inventory* [172]
Usability
OME [27] *Observational Measurement of Engagement* [39]
SUS [12] *System Usability Scale* [140]
NASA TLX [61] *Task Load Index* [47]
Custom Comfort Rating Likert Scale [34]
Touch
STQ [188] *Social Touch Questionnaire* [102]
NFT [131] *Need for Touch Survey* [148]
Emotion Regulation
ERQ [56] *Emotion Regulation Questionnaire* [110]
DERS [55] *Difficulty in Emotion Regulation Scale* [110]
Mindfulness
FFMQ [5] *Five Facet Mindfulness Questionnaire* [140]
TMS [90] *Toronto Mindfulness Scale* [140]
Addiction
RAS [178] *Reducer Augmenter Scale* [110]

Background – For papers describing a user evaluation, 36 papers (33%) did not specify participant pool details at all. The remainder described participants recruited as or from *university* students (n=23), some sort of *relationship*, *e.g.*, close friends, couple, family, a coworker (15), for experience related to a studied *activity* (3), *medical* patients or people with disability (2). Several (13) specifically screened participants for particular values, *e.g.*, females or people with diverse cultural backgrounds. Although some involved culturally diverse pools [15, 30, 41, 64, 197], only one [197] explicitly mentions its distribution. None studied or reflected on participant diversity.

Given diverse user groups represent unique needs and perspectives, we urge researchers to add details about their participant pools in the context of their research, which enables fellow researchers in gathering better insights and perspectives from their work.

5 MAJOR ADVANCES

AHSD research has advanced significantly over the past decade. In this section, we discuss these advances, organized and contextualized by our analysis.

5.1 Technological Advancements

We saw a wide range of sensing and actuation technologies used by AHSD researchers in the past decade (Section 4.7), with more variety in off-the-shelf bio-sensing than touch sensing. We note the emergence or growth of several commercial bio-sensors during this time (Affectiva Q Sensor, Empatica E4, Thought Technology Suite, Zephyr Performance Systems, MioFuse, RespiBAN, Bitalino, and Mindmedia NeXus-10), which reduced barriers to using physiological sensing as a means to understanding user affective state [38, 186], design new interactions [47, 108], and/or evaluate systems [92]. Availability of wearable consumer products such as the Doppel, Embr Wave, and Philips DTI-2 wrist band; the robotic toy Pleo; the Geomagic Touch X device; and tool-kits such as TECHTILE helped researchers test their hypotheses [48–50, 84, 175] and deploy their devices in-the-wild [39, 144], spending less time in the hardware design and development stage. Furthermore, miniaturized electronics, high-processing and low-power microprocessors, flexible circuits, and feasible seamless integration of short-range untethered communication have made custom fabrication more alluring and potentially linked to the emergence of custom designs of actuators, sensors, and devices, mostly in wearable form-factors [181]. Of newer haptic actuation techniques – Shape Memory Alloy, Electrical Muscle Stimulation, ultrasound and air jets – the last two allow for untethered mid-air tactile actuation, intriguingly surpassing the requirement of physical contact. Although not explicitly covered in our dimensional space, advancements in machine learning has influenced AHSD researchers in modeling user behaviors [21, 35, 113, 146, 150], processing and understanding sensor data [20, 42], and evaluating the impact [110] of their technologies.

5.2 Research Diversification

Although research efforts in the early decade concentrated on certain contribution foci, types, target participants, body locations, and actuation technologies, by the late decade this had diversified. For example, initially, many researchers studied how to communicate emotion mediated through technology, establishing requirements or developing designs targeting general populations, often instrumenting designs with vibrotactile actuation rendered on hands. Over time, research expanded to feature body awareness, emotion regulation support, and open-ended design and development, even as emotion communication work continued. There were also relatively more evaluation-centric works in the late decade. Although the hand still remains a commonly-studied body location for haptic interaction, by late-decade we noticed other body parts such as the abdomen, shoulder, and torso being studied. The devices involved include a diverse variety of haptic actuation techniques, occasionally with custom designs suiting the needs of the target application. The number of target populations which were themselves diverse increased, although still a small number; for example, with diversity in culture [15, 30, 64, 197] and accessibility needs [189].

Such diversification ensures that AHSD researchers are exploring the breadth of potential end-users and consequently expanding the applicability of their ideas; different groups can have different needs.

5.3 Interdisciplinary Research Clusters

The proportion of papers involving interdisciplinary collaborations ranged between 0–67% (mean = 35%) over the decade. Throughout this time the collaborators came together from a range of technical and non-technical fields. We recognize some notable examples of interdisciplinary research clusters including the WEHAB Lab at Stanford Univerisity [108–111] and AffecTech [30, 31, 85, 162, 168, 174–176] that accounted for 12 papers in our dataset. These clusters bring together researchers from different disciplines including HCI, Design, Computer Science, Psychology, Journalism, Healthcare, Neuroscience, Cognitive Science, and Engineering. Such collaborations facilitate building an ecosystem where diverse opinions are incorporated in all stages of research (formulation, design, development, and evaluation), circumventing disciplinary silos [103] and developing technologies that are grounded in practice [124].

5.4 Theoretical and Ethical Grounding

Incorporating theoretical grounding in AHSD research, researchers not only drew inspiration from commonly-known practices (*e.g.*, breathwork, mindfulness, and meditation), but also incorporated elements from evidence-based therapies (*e.g.*, CBT, DBT), and prominent models in psychology (*e.g.*, Gross Process Model). Although we see this as an advancement, we suggest researchers should apply such emotion theories and models thoughtfully, or else run the risk of choosing unsuitable emotion representations, overlooking nuanced details of user context, subjectivity, and the transient nature of emotion, leading to erroneous data and questionable computational models [16, 17]. We also noticed progressive and insightful discussions on ethics and data privacy in some papers where such considerations were included in the project ideation and design, as well as deployment and evaluation. The percentage of papers having such discussions remains low but seems to be increasing. Inclusion of verbatim comments from participants on ethical and privacy concerns around the future use of AHSD technology added insight and sets a healthy tone of research self-critique and considering design implications. We advocate for more such discussions with end users and stakeholders to assess the real-world implications and eventual impact of AHSD on targeted populations.

6 OPEN CHALLENGES

While there has been major progress, our analysis also consolidates evidence for open challenges in the field that need to be tackled for AHSD research to realize its potential.

6.1 Evaluating Long-term Impact with Rigor and Consistency

AHSD research is still in a developing stage, in which researchers are seeking to understand human touch, building custom hardware, exploring novel design and interaction paradigms, and employing different methods for conducting and evaluating research. In the decade we surveyed, evaluations were centred around user preferences, touch perception, and system performance using customized instruments and metrics (Section 4.8). Few researchers invest in longitudinal studies or studies outside the lab to assess and guide long-term usage and ecological validity of their inventions, and thereby a better chance at impact.

Deploying haptic technology in the wild is certainly not easy. Devices used for such deployments need to be robust, autonomous, and convenient to fix or replace if needed [79], a poor match for conceptual exploration embodied in low-fidelity prototypes. While any kind of novel technology has the same issue, haptic devices may be less forgiving and we do not have flexible prototyping platforms that ease this process. Deployed prototypes also need to be in a form-factor that is easy to use, resizeable [134], adaptable to the user's environment [87], unobtrusive [155], discreet and comfortable to wear (if wearable) [47]. Even when researchers manage a deployment, data sourced in the wild and outside of a structured experiment design always risks being hard to understand or dominated by unaccounted variables. We argue that at this point, the time, effort and risk involved are likely to generate deeper and more nuanced insights relating to the complexity of real-world use, and is crucial for real design evolution [88]. The process would be greatly aided by the emergence of prototyping platforms that target this kind of experimentation.

Reliable assessment of long-term use and health or behaviour impact requires standardized benchmarks, instruments, protocols, and metrics, themselves a major effort to develop and validate. Related to a need for more clinical evaluation (Section 4.8), we urge this community to embark on this necessarily interdisciplinary process.

We do believe that conducting clinical evaluation is a significant open challenge, deserving reflection. Many AHSD design efforts target a health outcome, whether for clinically affected populations or a matter of wellness; clinical evaluation is the current accepted mechanism for confirming or guiding such objectives. However, this step presents major obstacles to HCI researchers [89, 137]. Non-standardization of custom research-based haptic devices and relatively fewer options available for off-the-shelf deployment, and a general need for high robustness pose a technological barrier. Evaluations are designed and reported very differently: *clinical assessments* are usually longer-term, larger-N and tightly controlled study designs with specific populations focusing on health outcomes, whereas HCI research often focuses on single-session evaluations and design feedback. Clinical studies require clinical collaborators who can oversee the research and provide access to target populations. Institutionally, clinical trials are funded differently and have a more arduous ethics approval process. We hope that as design-based research matures, AHSD researchers targeting clinical populations will find ways to surmount these hurdles, involving clinical collaborators earlier in their design process [98], for greater validity and impact.

6.2 Translating Designs into Products

During our analysis, we saw several promising designs emerge; they varied in form factor, sensing and actuation technology, types of interaction, and targeted use cases. These designs, if commercialized, could have a positive impact on users' lives, facilitating emotion sensing, awareness, communication, and regulation; however, the commercialization of haptic technology faces hurdles.

While relevant sensing and actuation technologies are getting developed, they are not yet readily available, including low-cost, high-fidelity touch-sensing (pressure as well as multi-contact location), high-precision bio-sensing, and noiseless and compact haptic actuation technologies. Commercialized products generate large-scale personal sensor data, which needs to be securely stored, modelled and analyzed to prevent breaches and malicious use. Social and cultural acceptance of AHSD technologies is understudied, and public policies and general awareness regarding safeguards against malicious use are non-existent at this stage. Hence, translating such research into impactful products involves going beyond the design conceptualization, knowledge creation, and preliminary evaluation. It involves an interweaved collaboration between technology providers (*i.e.*, researchers), receivers (*i.e.*, end users, beneficiaries), and intermediary agents (*i.e.*, advisor, facilitator, consultants) [105] to create an ecosystem to iterate on, evaluate, and eventually deploy such designs in the wild. Such collaborations involve value sharing, consistent communication, and flexibility to adapt to the diverse needs of stakeholders and end-users [24, 79]. Although challenging, we do see some motivating examples of commercialized translations [79, 154] that can be used as an anchor for future work.

6.3 Including Diverse Perspectives

Our analysis highlights the concentration of AHSD research in the Global North, the skewed distribution of researcher backgrounds, increasing but sparse interdisciplinary collaborations, focus on *general* target populations, and the frequent involvement of non-specific participant pools often consisting of local university students. Given their geographic location, current researchers study this field in the context of Western-centric preferences, needs, culture, and socio-economic stature, *i.e.*, assuming easy access to smart devices, consistent internet connectivity, availability of personal space for interaction, high purchasing power, and most importantly, cultural and social acceptance of such technology.

These contexts might not be the same for certain demographics in the Global South (*e.g.*, low-income families, communities with social stigmas around interpersonal gender-specific touch and mental health) [132] and the Global North (*e.g.*, ethnic minorities) [156]. In order to conduct equitable AHSD work, researchers need to study the requirements of diverse users from different socio-economic backgrounds and incorporate their perspectives in their research conceptualization, design, and deployment. They need to analyze the impact of their technology's long-term use in situ and consider diversity while creating computational emotional models and generating affect datasets to avoid perpetuating systemic biases. This is a major challenge as access to such populations is often constrained and conducting such research might mean involving mediating stakeholders, multi-party collaborations, and conducting a dedicated ethnographic study [106] in addition to designing, deploying, and maintaining the technology.

6.4 Expanding Beyond the Personal

Based on the analysis of dimensions scope, social use and clinical use, spanning two facets (System and Usage Specifications), researchers are approaching AHSD research as a single-body problem, overlooking complex social dynamics (*e.g.*, community) and particular kinds of individual-other interactions (*e.g.*, patient-caregiver).

Consider an example of a robotic pet [15]: researchers need to consider its (1) social use: is it a personal device; how will it be incorporated in a social setting; will it have different form-factors, privacy and interaction modes based on social use-cases (informal vs formal, private vs public, friends vs family); (2) scope: will it interact dynamically in multiuser settings (*e.g.*, home, office, social gathering) and recognize and differentiate such interactions, and (3) clinical use: if used in a clinically-guided setting, will it offer clinicians a means to integrate evidence-based intervention, track progress, and update interactions based on need; will it support in-facility (private/public) use? With the focus on emotional health researchers need to go beyond personal interactions and design technologies with the context of the user's social and clinical needs. Further, researchers also need to study the target user's preference of form factor, body location, interaction, and scope, which will change based on the type of clinical or social use. Currently, these questions are understudied.

Although extremely relevant, clinically-guided and in-facility use of technology is not frequently studied or designed for, attributed to the fairly complex nature of such research [89, 137]. Use-cases, where users need regular clinical support in engaging with an AHSD technology, involves a challenge in the design and maintenance of technological infrastructures. Hospitals or healthcare facilities requiring in-facility installations of AHSD technologies also require considerable time and effort in the design and deployment of such technologies.

Furthermore, an individual's emotional journey is not supported only by themselves but also by their family members and peers [77]. Researchers need to consider these connections and work towards building AHSD ecosystems for community support which are broader than one-to-one emotion communication. We observed a few examples of haptic technologies envisioning group interactions involving more than two people [44, 80, 118, 155, 162, 164, 183] and while they mention multiuser scope for their devices, they did not formally evaluate such scenarios. Hence, research tailored for groups of more than two people remains a budding research avenue.

6.5 Humanizing Technologies

In our review, only a few papers studied their target audience before conceptualizing their design [64, 155, 197]; incorporated methods of co-designing to gain feedback [85, 166, 168]; fostered individual agency over the design, interaction, and decision-making [108, 144, 183]; and discussed the ethical and privacy implications of their proposed technology. Furthermore, for studying user preferences post-design, researchers often rely on methods like rating haptic perception and interaction on a scale. They rarely have in-depth discussions on why a user chose a particular haptic sensation or interaction to be more favourable. These choices during research formulation, design, and evaluation might narrow the focus on the technology rather than the user for which it is designed.

The AHSD research community needs to build an infrastructure moving from dehumanization to humanization [124], acknowledging that user needs, preferences and fears of such technology and eventual engagement and adherence stem from their socioeconomic context, cognitive and psychological models, past experiences, and other ontological origins. Based on these concepts, researchers can strive to develop open-ended designs [22, 69, 122, 144] instilling a sense of agency in users by providing them means to control, personalize, and adapt suiting their needs. They can also thoughtfully introduce such technologies using narratives and metaphors [16] relevant to target users while being open and clear about counter-intuitive effects and other ethical and privacy concerns.

During long-term deployment, where the technology may or may not be eventually handed off to the users, there can be a process of retraction – clarifying expectations prior to the study and easing the transition [161]. Lastly, in order to avoid generating an ecosystem of standalone devices, there should be a practice to build technology on top of existing consumer products using overlays, in-casings, covers, and pods [69]; this will not only help make the eventual product affordable for users but also ecologically sustainable.

7 LIMITATIONS

During the process of conducting this research, we made several decisions to inform our review scope, search methodology, dimensional space generation, and data analysis process. In this section, we reflect on the potential implications of these decisions.

7.1 Limited Time Period

While the design of Affective Haptic Systems has been studied since the late 1990s, our review only covers publications from the last 11.5 years (2010–mid-2021), chosen for that period's concentration of developments together with our analysis resources. 2021 was included as a half-year, compensated for through the use of ratios for comparison but under-representing some venues in the late-decade picture. Thus, while our analysis accurately represents significant developments, it does not capture the field's roots [11, 97].

7.2 Design- and Technology-oriented Scope

Our venue list prioritized design- and technology-oriented conferences and journals situated at the intersection of Haptics, Affective Computing, and HCI research. When making inclusion/exclusion choices for specific venues within the design focus, our goal was not comprehensiveness (in this scoping review) but representation. We thus identified choices based on our team's prior awareness based on over 20 years of interdisciplinary research in the area, inquiries, venue breadth and prominence (reasoning top places would attract broadly) and sample surveying for concentrations (impacting both the relevance of the venue to our search and our analysis resources) as we iteratively found a combination of venues that balanced representation of the three target disciplines with a manageable volume. Despite our best efforts, we inevitably missed candidates to sample-surveyed for high relevance, due to the bias of the team's experience and network. Given the prominence and centrality of the venues we did choose, we are confident that the major trends we found are trustable. However, caution should be exercised in relying on lower-N findings, which might rise or fall in more specialized venues related to them.

Our review did not explicitly include a social science lens which is an important perspective to look at AHSD research; however, it did capture social-science-oriented research (n=30) present within the venues we sampled, a testament to the interdisciplinary nature of these areas and venues.

7.3 Selective Search Keywords

We recognize that our *focus* keyword list may not have been exhaustive (*e.g.*, missing 'Affective Touch'), and this may have resulted in some relevant papers being missed. We did include a range of *generic* keywords to capture a broader scope and conducted a full-text keyword search (a relatively high-effort but rigorous screening task than meta-data or abstract search). Despite this, unintended exclusions are possible. Numbers could not be large, and should not undermine the representativeness of our sample corpus.

7.4 Design and Portrayal Subjectivity

Our analysis entailed many decisions which had to be made with varying degrees of subjectivity. Bias could have materialized while selecting venues and keywords, defining dimensions, organizing the dimensional space, and coding, particularly of more subjective dimensions (*e.g.*, contribution type and focus). We were conscious of data representation bias as we compressed the timeline in four-year clusters, reducing granularity and hiding annual outliers, but made this choice only after carefully considering all options and do not feel meaning was hidden.

8 CONCLUSION

We have analyzed a formative decade of research on the design of Affective Haptic Systems, as it appears in the most relevant 11 major ACM and IEEE venues. We contributed a multidimensional space of 38 descriptive dimensions within 8 facets, usable as a framework to analyze past and future research in this field. We provided a descriptive analysis of the past decade, covering research across key contributing venues, contextualized using our multidimensional framework. Our analysis enabled data-grounded identification and in-depth discussion of major advances and challenges, which we hope will help light the way for future researchers. This spotlight shows the strong foundation that past research has already laid, as well as the many opportunities for novel, innovative and ever more well-grounded research. We encourage future researchers to build on our advances to tackle these open challenges and contribute to ethical and deployable haptic affective technologies.

ACKNOWLEDGMENTS

We thank the members of the Sensory Perception and Interaction (SPIN) lab and Multimodal User Experience (MUX) research group at the University of British Columbia for their invaluable feedback throughout the research process. We extend our sincere thanks to Prof. Joanna McGrenere and Prof. John D. W. Madden for their insightful feedback on the early stages of the manuscript. We acknowledge the support of the Natural Sciences and Engineering Research Council of Canada (NSERC) Grant RGPIN 2018-04828.

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