

I Wandered Lonely in the Cloud: A Review of Loneliness, Social Isolation and Digital Footprint Data

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Abstract: The harm that social isolation and loneliness can have on physical, mental, and emotional well-being is now well evidenced. With social distancing and remote working now commonplace, the dangers of loneliness are ever more acute. Consequently, information technologies have taken on renewed importance to support healthy communication and reduce the negative impacts of social isolation. However, existing literature remains highly conflicted as to the relationship between technology use and its impact on loneliness. This is perhaps understandable: measures of loneliness have traditionally been examined within clinical settings, far removed from the everyday realities of computational interactions. Yet data logged about such interactions now offers potential to help identify isolation and loneliness and support those experiencing resulting health issues. We present a scoping review of this domain, focusing on detection of loneliness and social isolation through digital data. We interrogate a corpus of published articles from the HCI literature, identifying a series of methodological, epistemological, and ethical tensions therein, as well as emerging opportunities for future empirical study. We identify a need to examine such phenomena via actual behavioural data, rather than reliance on historical proxies such as age and gender, to help modernize our understanding of this growing social ill.


1 INTRODUCTION


"The world is the closed door. It is a barrier. And at the same time it is the way through. Two prisoners whose cells adjoin communicate with each other by knocking on the wall. The wall is the thing which separates them but it is also their means of communication. ... Every separation is a link."

The quote above by philosopher Simone Weil (1997) draws on Plato's concept of *metaxu*, meant here as something that both separates and connects simultaneously. It was originally intended to describe the challenge of communion with God, but its metaphor of a prison wall also serves as a useful analogy for how contemporary researchers describe technology and its effect on communication between people more generally. Recent works summarising loneliness and online social interaction have shown how information technologies, and in particular

interconnected digital devices, appear in the literature as both the cause of, and solution to, the growing issue of loneliness (Dunbar, 2021; Hertz, 2021). Much of the literature is therefore conflicted, illustrating that the causal relationship between the two categories is both complex and likely bi-directional; such that the aetiology of loneliness is at least partially context dependent. Technology transforms social relations, and in doing so, creates new opportunities for alienation and communion alike.

Despite the complexity involved in potential manifestations of loneliness, research conducted by social neuroscientists (Cacioppo and Patrick, 2008) provides scientific evidence that loneliness causes physiological events that wreak havoc on our health. Persistent loneliness leaves a mark via stress hormones, immune function and cardiovascular function (Knox and Uvnäs-Moberg, 1998) with a cumulative effect that brings health outcomes similar

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to being a smoker (Holt-Lunstad *et al.*, 2010). Furthermore, loneliness exacerbates the risk of experiencing additional subsequent problems and altering behaviour insofar as it increases the likelihood ‘of indulging in risky habits such as drug taking and plays a role in mental disorders such as anxiety and paranoia’ (Griffin, 2010). Despite this, many people experiencing loneliness do not interface with medicalized settings; and few receive clinical diagnosis or support. Due to the hidden nature of the problem, estimates of loneliness are often absent from national statistics despite potential to inform social policy. As a result, researchers have often turned to demographic proxies for loneliness, with much work throughout the 20th century seeking to theorise the phenomena, and the nature of those people predisposed to it. In particular, the elderly (over 65s) and disabled, widely cited in academia as being most affected, underpin most analyses of loneliness prevalence. Yet the UK’s Office of National Statistics (ONS, 2018) and BBC, via the world’s largest empirical study of loneliness (BBC, 2019), recently showed that loneliness is far from constrained to these communities; and affects the population in far more ways than previously recognised

Recently, the issue has been further exacerbated by Covid-19, and our increasing exposure to conditions conducive to loneliness (Bu *et al.*, 2020). Dramatic societal change, lockdowns, and enforced social distancing has spawned a flurry of research to help identify those most at risk of loneliness and its myriad health consequences (Ernst *et al.*, 2022). Yet, the mass transformation of work and socialization into increasingly online settings has also created opportunity for researchers: digital identification of those at risk. Whether in cases where digital technology exacerbates loneliness or in situations it diminishes it, human-computer interactions leave behind a rich corpus of digital logs. Such digital footprint data, if handled responsibly, can offer new avenues to help identify, characterize, and intervene in this “wicked problem”. The development of big data and ubiquitous digital architectures to log everything from library records, transport movements, health records, social interactions and even shopping habits illustrates the wide range of siloed information available; data that might be harnessed to better understand vulnerability to loneliness and to direct social policy accordingly. With such potential, of course, comes risk: approaches that depend on indirect, closed, or proprietary data sources introduce new methodological, ethical, and privacy challenges, otherwise absent in clinical settings.

The overall aim of this work is therefore to establish the contexts in which digital data are being used when identifying people experiencing social isolation or loneliness, or where data are being inadvertently created by the interactions of those people experiencing loneliness (particularly those who are doing so in populations not typically recognised within clinical settings). Unlike review papers that have attempted to map the efficacy of digital technologies as loneliness interventions from a public health perspective (Shah *et al.*, 2019; Ibarra *et al.*, 2020), we provide a scoping review of how social isolation and loneliness interventions are already conceived, discussed, and enacted within the computing literatures. By examining epistemological and methodological bases of previous research we aim to expose some of the underlying intellectual commitments and assumptions currently being made in the field and contextualize ongoing debate. We first outline the methodology and scoping approach used to achieve this, before discussing emerging genres in the field and the key analytical differences that separate researchers. Finally, we discuss emerging issues and empirical gaps in the domain that, if addressed, can serve as the basis for addressing this phenomenon.

2 METHODOLOGY

While ‘loneliness’ and ‘social isolation’ are well accepted terms in everyday usage, definitions in academic contexts vary significantly by scientific discipline and empirical focus. Significant existing work has sought to characterise loneliness and social isolation through study of their respective aetiologies from a public health perspective (Holt-Lunstad, 2017; Elovainio *et al.*, 2017; Steptoe *et al.*, 2013; Lubben, 2017). Various constructs are described in the literature suggesting interconnectedness between the conditions; and in much work the terms ‘loneliness’ or ‘social isolation’ are used interchangeably - particularly in research which does not aim to conceptualise the respective concepts. Yet there is limited consensus here, with other research viewing the conditions as entirely distinct and to be considered independently (Matthews *et al.*, 2016); and in psychological and clinical research it is far more common to differentiate the constructs. Social isolation is typically described as the circumstance of being physically alone or otherwise detached from contact with friends, family, or society; Loneliness, in contrast, is described as a negative psychological response to such situations, commonly portrayed as

‘a subjective, unwelcome feeling of lack or loss of companionship... [occurring] when we have a mismatch between the quantity and quality of social relationships that we have, and those that we want’ (Perlman and Peplau, 1981). Academic definitions are contested for both terms, with some authors speaking of multiple sub-types of loneliness (Weiss, 1975), yet a separation is commonly recognised between them. As our intention is to synthesize literature around these concepts, we do not challenge such definitions - while the overlapping of language creates challenges for comprehensive summarisation of the field, it also highlights the need for consilience and transdisciplinarity to support further advances.

Archetypal definitions of loneliness and social isolation primarily came from diagnostic scales developed in the latter part of the 20th century. Weiss (1975) saw ‘social loneliness’ as a lack of or negative change in social connections below a desired level, whereas ‘emotional loneliness’ was a lack of deep, meaningful (i.e. romantic or familial) connection. This multidimensional approach to the study of loneliness is not, however, reflected in the widely used UCLA Loneliness Scale (Russell, 1996) which treats loneliness as a unidimensional construct. While this approach has been contested (Marangoni and Ickes, 1989), Russell et al. (1984) have argued that, despite different forms existing, that the UCLA scale adequately summarises these different loneliness states. UCLALS is the most widely used measurement for loneliness, but several alternative well-cited measures exist. Almost uniformly, however, these predate widespread adoption of the Internet and digital devices - whether de Jong Gierveld’s Scale (De Jong-Gierveld, 1987), the Social and Emotional Loneliness Scale for Adults (DiTommaso and Spinner, 1993), Differential Loneliness (Schmidt and Sermat, 1983) or the Loneliness Rating Scale (Scalise et al, 1984).

One of the key, outstanding questions for digital identification of loneliness, is therefore the extent to which present-day research should revisit such measures, given the rapid integration of technology into our daily lives over the past two decades (e.g., mobile private messaging, social networking, and livestreamed video). The impact the digital world has had on our experience of loneliness and social isolation remains unclear; do traditional metrics still hold; and to what extent have traditional proxies become anachronistic? Loneliness has predominantly been identified in clinical settings through surveys and self-diagnosis, or via direct medical assessment. Do such environments overlook people in need of support but who do not seek out practitioners, either

being unable or stigmatised from doing so? To consider questions of this nature, Munn et al. (2018) have advanced scoping reviews as useful tools to examine emerging evidence; especially when it is still unclear what other, more specific questions can be valuably posed and addressed by future empirical work. Such reviews aim to not only report on evidence that informs practice in the field, but to consider the way research has been conducted, and in particular ‘in contrast to traditional literature reviews scoping reviews are informed by an a priori protocol; Are systematic; Aim to be transparent and reproducible; and ensure data is extracted and presented in a structured way’ (Munn et al., 2018).

This scoping review focuses on two databases containing peer-reviewed papers in computing and its associated sub-disciplines, the Association for Computing Machinery (ACM) and the IEEE Xplore (IEEE) digital libraries respectively. Both libraries were searched, isolating abstracts containing the terms ‘loneliness’ or ‘social isolation’. This produced a total of 401 results, and the resulting corpus was screened for non-English, inaccessible, or non-peer reviewed articles or conference papers. Each article was then reviewed to ensure that social isolation or loneliness was not peripheral but a relevant empirical or conceptual focus of the work. Papers either: (1) identified social isolation or loneliness as part of their sampling procedure; (2) used social isolation or loneliness as a dependent or independent variable within analysis; or (3) social isolation or loneliness was specifically being explored or researched through an inductive or conceptual approach. This process is summarised via the PRISMA diagram in Figure 1. The final output corpus yielded 52 articles, which were taken forward to fine-grained analysis. Each article was decomposed, and re-summarised into a short commentary before then being analysed in relation to a series of methodological questions. Answers to these questions were tabulated, serving as the basis thematic identification discussions between the research team, who collaboratively identified genres and epistemological commitments made by the works.

The methodological research questions considered are: (1) Is the work empirical (data gathering) or conceptual? (2) Data provenance - if data are gathered what is collected and how? (3) Sampling - who is the focus of the research / who is thought to be lonely? (4) Does the study aim to identify people experiencing issues, intervene to help people, or to conceptualize what loneliness is? (5) Is loneliness or social isolation measured and if so, how; is it a pre-existing measure or newly developed? (6)

Is an expert identified within labelling (or not); who gets to identify those being labelled lonely?; (7) What methods were used to analyse loneliness data generated? (8) what metadata is likely to exist as part of the measures chosen e.g., social network data, spatial data, or time series data; and (9) What constitutes success and who are the beneficiaries? The answers to these questions were then used to (a) identify genres of work with clustered formulations of loneliness problems/challenges addressed via digital technology; (b) to examine contrasting methodology and epistemology of studies in the field, and (c) to indicate promising avenues for future research.

3 ANALYSIS

52 papers were included in the final corpus. Figure 1 shows the earliest three papers from the corpus (Zhang, 2009; Zhou et al., 2009; Waterworth and Ballesteros, 2009) appeared in 2009, with a gradual annual increase until 2020, which saw 12 relevant papers published (search conducted 04/2021). 37 articles used established loneliness measures, of which 16 used the UCLA loneliness scale. The vast majority of papers that measured loneliness or social isolation directly used survey questions using Likert Scales or specific protocols (e.g., UCLA or De Jong Gierveld scales). Those papers that did not use established measures did so primarily due to an inductive or exploratory qualitative focus, or because of emphasis on intervention development (e.g. use of robots) rather than intervention assessment.

A striking feature of the corpus is that two specific demographics dominate the empirical work (the elderly – 19 papers; and student populations – 9 papers). Such is their emphasis within the corpus that in the following section we examine each of these categories in turn as distinct genres. It is, however, worth noting that this bimodal split is based upon a priori demographic sampling decisions rather than selections made due to indicators of loneliness or social isolation. Most students graduate in their early twenties, whereas retirees (particularly those in nursing homes, a common setting of loneliness research) normally exceed 65 years. This >40-year gap reflects a large section of the populace absent from research. Within the corpus 15 articles explicitly sought to develop methods to identify lonely or socially isolated people. 12 papers focused explicitly on loneliness or social isolation interventions. The remainder contained a mixture of inductive, exploratory, and hypothetico-deductive

approaches in which loneliness or social isolation featured.

In the following section, we describe genres resulting from the analysis. Genres are structured from clusters of research that frame problems of loneliness, isolation, and digital technology in similar ways. Given the recent emergence of much of the work and the inevitable overlapping of some themes within papers the genres should not be thought of as internally consistent movements to which the authors are aligned, rather the aim here is to illustrate similarity of agendas and offer a lens through which some of the key debates can be seen. There are five identifiable genres within the corpus that describe all but one paper (related to testing a loneliness scale in Italy (Senese et al., 2020), albeit unrelated to digital footprints); these are now discussed in turn.

Genre 1: The Elderly

18 papers contained an explicit focus on loneliness or social isolation in the elderly, making it the largest genre in the corpus (Broadbent et al. 2018; Eldib et al., 2015; Yang and Bath, 2018; Pedell et al., 2010; Baecker et al., 2014; Light et al., 2017; Zadeh et al., 2020; Martinez et al., 2017; Austin et al., 2016; Ring et al., 2013; Ha and Hoang, 2017; Bacciu et al., 2016; Noguchi et al., 2018; Chang and Kalawsky, 2017; Yoshida et al., 2018; Mulvenna et al., 2017; Petersen et al., 2013; Waterworth et al., 2009). In these, older people are identified as an at-risk group due to the intersection of multiple life events - for example: leaving the workforce through retirement; losing family through bereavement; having children leave home; or being forced into care homes for health reasons. In each case, elderly people see transformations of their social networks, losing opportunities for meaningful social interaction. Such features of ageing are well known; and because elderly populations often tend to have limited geospatial mobility and higher chances of interfacing with medicalised settings, visibility of loneliness and isolation is increased, allowing for more easily targeted interventions. It is therefore understandable that this genre also features the highest relative share of interventions detailed within the corpus. In clinical practice, algorithmic risk-based estimates of loneliness in the elderly are likely to perform well, particularly where personal data is available and where trust in the robustness and explainability of the method can be secured. Indeed, recent work showcases machine-learning approaches already yielding reliable performance (Yang and Bath, 2018). However, current risk-based methods typically depend on presentation or referral within a clinical setting.

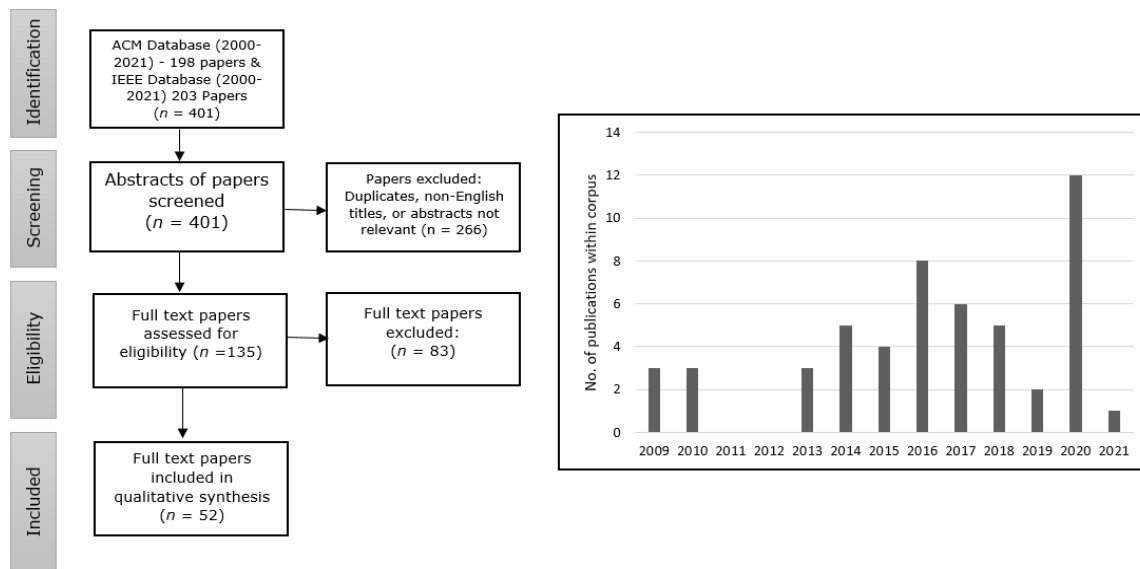


Figure 1: (Left) Review Screening Process; (Right) Yearly breakdown of publications within final corpus.

Sampling issues of this nature raise concerns about potentially under-served sub-populations (e.g., those living alone), not evident in clinical settings; and who may be more effectively identified via non-traditional means (e.g., via digital footprint data).

Genre 2: The Student Experience

Academics have historically been criticised for an overreliance on sampling students as part of psychological and clinical research, but in this instance, the need for research on the experience of loneliness within student populations is of clear relevance. Students often move cities to attend university, with a sizeable minority moving internationally to an unfamiliar place to live and work amongst unfamiliar people. A range of papers use students as an explicit empirical focus or do so implicitly by only sampling from student populations (Fuentes et al., 2016; Joyner et al., 2020; Zhou et al., 2020; Zhang, 2010; Kindness et al., 2013; Lu and Yao, 2010; Zhou et al., 2009; Xu et al., 2015; Ferrer et al., 2020). Migration is a key cause of loneliness for this cohort. Students can be made lonely and isolated via their own movement, which fragments prior social networks (in hope of the formation of new ones), while limiting familial support structures. The methodological tendency within this genre tends towards consideration of online data sources useful for identification of mental health problems, whereas for the elderly genre research methods tend to focus on interventions, and data generated by physical technology in situ. Most papers in the corpus leverage established survey measures to identify loneliness;

but only three papers seek to identify loneliness as a dependent variable with the remainder focusing more on interpersonal relationships and wellbeing. One article (Zhou et al., 2020) notes, for instance that ‘Previous studies on loneliness have mainly focused on using questionnaire-based loneliness scales, e.g., UCLA scale, for the measurement of loneliness. Nevertheless, the lonely may prevent reporting their real conditions since they are afraid of information disclosure, discrimination, unfair treatment, thus it makes the information accumulated by these questionnaires unreliable.’ The challenge of reliable sampling frames again raises the possibility to supplement traditional approaches using alternative health surveillance methods (particularly those that examine social network or communication data - e.g., classroom collaboration network data). Incorporating behavioural observation data with surveys is likely to help scale prevalence estimates of loneliness across broader populations (behavioural vs demographic proxies) although risk-based probabilistic approaches are better suited to population prevalence estimation than deterministic assessments used in clinical practice. There is likely a useful bifurcation in data and methods used for population and individual level assessment worthy of further inquiry, particularly due to the sensitive nature of social network data.

Genre 3: Online Services, the Web, and Apps as Windows into the Experience of Loneliness

A growing number of papers (Brueckner, 2020; De Choudhury et al., 2014; Joseph et al., 2014; Weinert et al., 2014; Jeong et al., 2015; Taylor et al., 2017;

Burke et al., 2010; Ananto and Young, 2021; Jeong et al., 2016; Galunder et al., 2018; Pulekar and Agu, 2016; Rabani et al., 2020; Kaur et al., 2020; Wu et al., 2016; Lu and Yao, 2010) draw on diverse data sources being used from popular Web and Smart Device applications such as (messaging, phone calls, web browser logs, gaming, teleworking applications, Facebook, Instagram, Twitter, Grindr, and Amazon Kindle) to explore loneliness within the respective user populations. 7 articles in the corpus used established survey measures, of which 5 applied the UCLA survey. This genre is characterised by big data and behavioural analytics approaches, with commercial Web services often being repurposed for prosocial reasons. For example Gao et al. (2019) correlate usage of a dating website with loneliness measures, regressing features engineered from profiles, postings, and check-ins with ‘surveys [of] psychological states by four professional questionnaires measuring different kinds of mental disorders: depression, loneliness, anxiety, and stress’. Mixed method approaches of this nature, that combine structured data (e.g. clinical surveys) with wide-ranging and often unstructured social network data, hold promise for prevalence risk estimates within their user population; though are likely to introduce potentially hidden forms of survivorship bias that require triangulation within a broader population before they could be validated. The linking of social network usage (both time spent, words/sentiments used, and people contacted) is a common area of study amongst this genre. An illustrative example can be seen in a study (Kaur et al., 2020) of over 140 million tweets to analyse personality insight, emotion, and sentiment analysis in relation to social isolation during the pandemic. The premise is a straightforward one: how we describe ourselves and who we interact with is liable to change throughout our lives, with such transitions being mirrored in our digital footprints online. If this is true, then as the authors note, aggregated results might be used to support ‘a public health indicator to anticipate the possibility of social isolation and design health policies accordingly.’ However, despite showing initial promise, further work is needed to evaluate the efficacy of such claims, particularly where approaches can be replicated alongside robust clinical measures.

Genre 4: Physical Technology, Robots, and Anthropomorphic Interactions

A series of papers (Lazányi, 2016; Eyssel and Reich, 2013; Lou et al., 2019; Li et al., 2020a; Li et al., 2020b) focus on the creation or delivery of physical

resources, often robotic interventions, to help alleviate social isolation and/or loneliness. The focus of these papers is primarily development of new technology rather than identification of loneliness. The genre emphasises intervention (or what has been called ‘prosocial interaction design’ – Harvey et al., 2014), and specifically focuses on transforming the physical environment around people likely to experience loneliness. However, unlike interaction design strategies that aim to pair people with other people to foster communion and thus remove loneliness, a far greater emphasis is placed on non-human subjects and mastery of anthropomorphism. The papers tend to focus on dyadic solutions to loneliness i.e., creating a surrogate partner (either high fidelity humanoids or non-humans such as pets with human-like features – Lou et al., 2019) with whom a person can form meaningful attachment. Though Eyssel and Reich (2013) found that people experiencing loneliness may be more likely to anthropomorphise robots, Li et al. (2020a; 2020b) find that the relationship is not so clear and that a more nuanced understanding of what loneliness is can better serve to predict efficacy of interventions, specifically through reference to ‘trait’ versus ‘state’ loneliness. Whilst this concept - effectively representing chronic and temporary loneliness - is not unique in clinical literature, it is within the papers identified within this corpus and suggests distinct data sources could be considered for more general measures. This genre points to the idea that multidimensional measures of loneliness in the digital world may help to develop subsequent interventions, it is therefore worthy of further research, particularly where new measures account for online experience and can be paired with longitudinal clinical outcomes.

Genre 5: Edge Communities

The smallest identifiable genre, covering 4 papers, considers differing edge communities - people living in more extreme physical or mental conditions, including refugees (Almohamed and Vyas, 2016), mental health patients (Bears et al., 2020), cancer patients (Jacobs et al., 2015), ‘seafarers’, remote communities in Greenland, and welfare claimants in Northeast England (Jensen et al., 2020). Though these groups represent relatively small sub-sets of the broader population, they each nonetheless exhibit distinct behavioural characteristics which might prove useful in 1. generalized identification; and 2. understanding variance across sub-populations. All are characterised by transience i.e., people not expected to remain in a lonely state in the long term. They are, as Jensen et al. (2020) note, going through

‘digital liminal’ states and thus the data generated by these people is likely to experience sharp phase transitions. Given these demographics remain more likely to experience loneliness at some point than the general population they serve as excellent case studies for designing health surveillance to understand broader prevalence statistics. Further research is required to identify how digital footprints align across liminal populations and whether metadata can be ethically obtained, especially given the precarious lives these groups experience.

3.1 Epistemological and Methodological Tensions

Tension 1 - Sampling and Exclusion: As noted earlier, research into loneliness and social isolation has to date heavily emphasised student and elderly populations. Some exceptions exist, but children and those in the range 21-60 have seldom been considered as research subjects for digital footprints and loneliness – a clear gap in the domain, made all-the-more pressing due to changes in daily working environments since COVID-19. Such an omission is partly for good reason: students and the elderly are stable populations, relatively accessible, and with well reported challenges. Nonetheless, the corpus excludes a huge portion of the average human life course. Loneliness and social isolation do not, of course, act across such neat demographics in practice. A solution may be to develop encompassing prevalence estimates derived from digital footprint data.

Tension 2- Validity of Loneliness Measures: The use of traditional scales, for example the UCLA or De Jong Griefveld scales, may be anachronistic with the forms of loneliness and social isolation occurring in the modern world. Digital technology is enabling new forms of rich and multi-faceted communication that do not depend on being in the same place at the same time. While the number of “contacts” we maintain has increased due to technological innovations, has this impacted on the shared social experience that prevents loneliness? And is this divergence between isolation and loneliness represented in the metrics currently used? As most influential scales were created prior to widespread Internet and smartphone adoption they have little to say about the aspects of social life now integral to work, play, and socialisation. The notion of mixed modalities of loneliness is something many authors note, but it is rarely studied due to the absence of standardised measures.

Tension 3 – Clinical versus Non-clinical Populations and Non-overlapping Data Sets: This tension is best illustrated by the contrast between genre 1 (the elderly) and genre 3 (online services and their associated big data). In the former, researchers have excellent access to a population known to be more likely lonely and who also likely frequent clinical settings. This demographic is therefore easier to identify through formal methods, but they are likely to have sparser digital footprints when compared with the broader populace that could be used for prevalence estimates. In contrast, online services such as social media have rich behavioural data illustrative of the interactions of lonely people and often these data cut across multiple demographics but pairing clinical measures is harder from a methodological and ethical perspective. Here, again care must still be taken to avoid exclusionary bias. Machine learning models retain biases inherent to the datasets they are trained with - and the availability of digital footprint data (or lack thereof) in representative communities such as the elderly must be considered. As such hybrid approaches seem a sensible solution – there is no one size fits all.

4 CONCLUSIONS

Via this scoping review, several tensions, research gaps and opportunities have been evidenced. Unexpectedly, it is gaps in the current literature, that potentially offer the most insight, indicating the impact digital footprints might have in improving loneliness prevalence estimation and modernizing its characterization. If leveraged responsibly, behavioural datasets promise to advance understanding for public health and policy and help augment a domain that has historically been forced to rely on coarse proxy data such as age and general or limited clinical records. Social network, mobility, and behavioral data all hold potential to support more-encompassing prevalence statistics of loneliness. Yet our scoping analysis highlights several challenges and tensions therein, issues that require continued scholarly attention. The following opportunities, if invested in, may help attend to these challenges, consolidate knowledge and advance maturity in the field:

Opportunity 1 – Sampling - The Need for Longitudinal Study through the Life Course: To make use of digital footprints researchers need to ensure validity and efficacy, through ‘ground truths’ - labelling of loneliness in individuals, that can be

paired to rich, observed behavioural data to determine both indicators and antecedents. This is especially relevant for middle-aged populations, who occur far less in clinical contact records. Furthermore, inter- and intra- person reliability measurements for loneliness surveys are rarely conducted yet would be highly valuable when pairing longitudinal digital footprints for the purpose of identification and risk-based prevalence estimates.

Opportunity 2 – Validity - Studying Digital Loneliness as its Own Experience: distinct from the loneliness measured and identified via surveys such as the UCLA, the field should encourage research of extended multi-dimensional measures and identification tools to recognise new experiences across mixed modalities. Our contact lists are ever extending – however it is a lack of socially-shared interactions which may be at the root of modern experiences of loneliness.

Opportunity 3 – Make Data Useful, Open and Transparent: As evidenced in Genre 3, much of the data being studied by researchers is proprietary, closed, and often commercial in nature. Notwithstanding privacy concerns the need for open data is a pre-requisite if the field is to develop. In addition, only 3 papers include any spatial data, this is surprisingly low because mobility/movement tracking is often cited as a solution for loneliness monitoring (particularly in the elderly). Broader engagement of relevant communities, co-creation of research studies, and focus on initiatives that engage sufferers through open and transparent data sharing, are required not only if we are to model loneliness effectively – but if we are to generate practical interventions from model explanations, with real-world impact. Kurt Vonnegut once reportedly said *‘What should young people do with their lives today? Many things, obviously. But the most daring thing is to create stable communities in which the terrible disease of loneliness can be cured.’* To this we might add, identifying and supporting those in need is a first key step.

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REFERENCES

- Almohamed, A., & Vyas, D. (2016). Designing for the Marginalized: A step towards understanding the lives of refugees and asylum seekers. In Proceedings of the 2016 acm conference companion publication on designing interactive systems (pp. 165-168).
- Ananto, R. A., & Young, J. E. (2021). We can do better! an initial survey highlighting an opportunity for more HRI Work on loneliness. In Companion of the 2021 ACM/IEEE International Conference on Human-Robot Interaction (pp. 457-462).
- Austin, J., Dodge, H. H., Riley, T., Jacobs, P. G., Thielke, S., & Kaye, J. (2016) A smart-home system to unobtrusively and continuously assess loneliness in older adults. IEEE journal of translational engineering in health and medicine, 4, 1-11.
- Baecker, R., Sellen, K., Crosskey, S., Boscart, V., & Barbosa Neves, B. (2014). Technology to reduce social isolation and loneliness. In Proceedings of the 16th international ACM SIGACCESS conference on Computers & accessibility (pp. 27-34).
- Bacciu, D., Chessa, S., Ferro, E., Fortunati, L., Gallicchio, C., La Rosa, D., ... & Vozzi, F. (2016). Detecting socialization events in ageing people: The experience of the doremi project. In 2016 12th International Conference on Intelligent Environments (IE) (pp. 132-135). IEEE
- BBC (2019) BBC Radio 4 - The Anatomy Of Loneliness - Who Feels Lonely? [Online] Available at: <https://bbc.in/3NOjIey> [Accessed 15 May 2021].
- Bearse, P., Manejwala, O., Mohammad, A. F., & Haque, I. R. I. (2020). An Initial Feasibility Study to Identify Loneliness Among Mental Health Patients from Clinical Notes. In 2020 3rd International Conference on Information and Computer Technologies (ICICT) (pp. 68-77). IEEE.
- Broadbent, E., Ahn, H. S., Kerse, N., Peri, K., Sutherland, C., Law, M., ... & Pandey, A. K. (2018). Can robots improve the quality of life in people with dementia?. In Proceedings of the Technology, Mind, and Society (pp. 1-3).
- Brueckner, S. (2020). Captured by an Algorithm. In ACM SIGGRAPH 2020 Art Gallery (pp. 458-459).
- Bu, F., Steptoe, A., & Fancourt, D. (2020). Who is lonely in lockdown? Cross-cohort analyses of predictors of loneliness before and during the COVID-19 pandemic. Public Health, 186, 31-34.
- Burke, M., Marlow, C., & Lento, T. (2010). Social network activity and social well-being. In Proceedings of the SIGCHI conference on human factors in computing systems (pp. 1909-1912).
- Cacioppo, J. T., & Patrick, W. (2008). Loneliness: Human nature and the need for social connection. WW Norton & Company.
- Chang, A. S., & Kalawsky, R. S. (2017). Future configurable transport for the ageing population. In 2017 7th International Conference on Power Electronics Systems and Applications-Smart Mobility, Power Transfer & Security (PESA) (pp. 1-5). IEEE.

- De Choudhury, M., Counts, S., Horvitz, E. J., & Hoff, A. (2014). Characterizing and predicting postpartum depression from shared facebook data. In Proceedings of the 17th ACM conference on Computer supported cooperative work & social computing (pp. 626-638).
- de Jong-Gierveld, J. (1987). Developing and testing a model of loneliness. *Journal of personality and social psychology*, 53(1), 119.
- DiTommaso, E., & Spinner, B. (1993). The development and initial validation of the Social and Emotional Loneliness Scale for Adults (SELSA). *Personality and individual differences*, 14(1), 127-134.
- Dunbar, R., 2021. *Friends: Understanding the power of our most important relationships*. Hachette UK.
- Eldib, M., Deboeverie, F., Haerenborgh, D. V., Philips, W., & Aghajan, H. (2015). Detection of visitors in elderly care using a low-resolution visual sensor network. In Proceedings of the 9th International Conference on Distributed Smart Cameras (pp. 56-61).
- Elovainio, M., Hakulinen, C., Pulkki-Råback, L., Virtanen, M., Josefsson, K., Jokela, M., ... & Kivimäki, M. (2017). Contribution of risk factors to excess mortality in isolated and lonely individuals: an analysis of data from the UK Biobank cohort study. *The Lancet Public Health*, 2(6), e260-e266.
- Ernst, M., Niederer, D., Werner, A. M., Czaja, S. J., Mikton, C., Ong, A. D., ... & Beutel, M. E. (2022). Loneliness before and during the COVID-19 pandemic: A systematic review with meta-analysis. *American Psychologist*.
- Eyssel, F., & Reich, N. (2013). Loneliness makes the heart grow fonder (of robots)—On the effects of loneliness on psychological anthropomorphism. In 2013 8th acm/ieee international conference on human-robot interaction (hri) (pp. 121-122). IEEE.
- Ferrer, M., Mancha, V., Chumpitaz, M., Begazo, J., & Chauca, M. (2020). Characterization of the impact of SARS-CoV-2 pandemic social isolation on the psychosocial well-being of public university students, based on the GHQ-28 Scale. In Proceedings of the 4th International Conference on Medical and Health Informatics (pp. 295-301).
- Fuentes, C., Rodríguez, I., & Herskovic, V. (2016). Making Communication Frequency Tangible: How Green Is My Tree?. In Proceedings of the TEI'16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction (pp. 434-440).
- Galunder, S. S., Gottlieb, J. F., Ladwig, J., Hamell, J., Keller, P. K., & Wu, P. (2018). A VR ecosystem for telemedicine and non-intrusive cognitive and affective assessment. In 2018 IEEE 6th International Conference on Serious Games and Applications for Health (SeGAH) (pp. 1-6). IEEE.
- Gao, X., Zhang, C., Ma, L., Wang, Y., Wang, J., & Zhang, D. (2019). Correlating msm's mental health with usage behaviors on msm-specific social applications. In 2019 IEEE SmartWorld, Ubiquitous Intelligence & Computing, Advanced & Trusted Computing, Scalable Computing & Communications, Cloud & Big Data Computing, Internet of People and Smart City Innovation IEEE.
- Griffin, J. (2010). *The lonely society?*. Mental Health Foundation.
- Ha, T. V., & Hoang, D. B. (2017). An assistive healthcare platform for both social and service networking for engaging elderly people. In 2017 23rd Asia-Pacific Conference on Communications (APCC) (pp. 1-6). IEEE.
- Harvey, J., Golightly, D., & Smith, A. (2014). HCI as a means to prosociality in the economy. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (pp. 2955-2964).
- Hertz, N. (2021). *The lonely century: how to restore human connection in a world that's pulling apart*. Currency.
- Holt-Lunstad, J. (2017). The potential public health relevance of social isolation and loneliness: Prevalence, epidemiology, and risk factors. *Public Policy & Aging Report*, 27(4), 127-130.
- Holt-Lunstad, J., Smith, T. B., & Layton, J. B. (2010). Social relationships and mortality risk: a meta-analytic review. *PLoS medicine*, 7(7), e1000316.
- Ibarra, F., Baez, M., Cernuzzi, L., & Casati, F. (2020). A systematic review on technology-supported interventions to improve old-age social wellbeing: loneliness, social isolation, and connectedness. *Journal of healthcare engineering*, 2020.
- Jacobs, M. L., Clawson, J., & Mynatt, E. D. (2015). Comparing health information sharing preferences of cancer patients, doctors, and navigators. In Proceedings of the 18th ACM Conference on Computer Supported Cooperative Work & Social Computing (pp. 808-818).
- Jensen, R. B., Coles-Kemp, L., Wendt, N., & Lewis, M. (2020). Digital liminalities: Understanding isolated communities on the edge. In Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (pp. 1-14).
- Jeong, E. J., Kim, D. J., & Lee, D. M. (2015). Game addiction from psychosocial health perspective. In Proceedings of the 17th International Conference on Electronic Commerce 2015 (pp. 1-9).
- Jeong, E. J., Kim, D. J., Lee, D. M., & Lee, H. R. (2016). A study of digital game addiction from aggression, loneliness and depression perspectives. In 2016 49th Hawaii International Conference On System Sciences (HICSS) (pp. 3769-3780). IEEE.
- Joseph, K., Carley, K. M., & Hong, J. I. (2014). Check-ins in "Blau Space" Applying Blau's Macrosociological Theory to Foursquare Check-ins from New York City. *ACM Transactions on Intelligent Systems and Technology (TIST)*, 5(3), 1-22.
- Joyner, D. A., Wang, Q., Thakare, S., Jing, S., Goel, A., & MacIntyre, B. (2020). The synchronicity paradox in online education. In Proceedings of the Seventh ACM Conference on Learning@ Scale (pp. 15-24).
- Kaur, S., Kaul, P., & Zadeh, P. M. (2020). Study the impact of covid-19 on twitter users with respect to social isolation. In 2020 Seventh International Conference on Social Networks Analysis, Management and Security (SNAMS) (pp. 1-6). IEEE.

- Kindness, P., Mellish, C., & Masthoff, J. (2013). How virtual teammate support types affect stress. In 2013 Humaine Association Conference on Affective Computing and Intelligent Interaction (pp. 300-305). IEEE.
- Knox, S. S., & Uvnäs-Moberg, K. (1998). Social isolation and cardiovascular disease: an atherosclerotic pathway?. *Psychoneuroendocrinology*, 23(8), 877-890.
- Lazányi, K. (2016). Investing in social support—Robots as perfect partners?. In 2016 IEEE 14th International Symposium on Intelligent Systems and Informatics (SISY) (pp. 25-30). IEEE.
- Li, S., Ni, S., & Peng, K. (2020a). The Role of Good Human Uniqueness in Social Robot Anthropomorphism Influenced by Chronic Loneliness. In 2020 IEEE International Conference on Human-Machine Systems (ICHMS) (pp. 1-6). IEEE.
- Li, S., Xu, L., Yu, F., & Peng, K. (2020b). Does trait loneliness predict rejection of social robots? In Proceedings of the 2020 ACM/IEEE International Conference on Human-Robot Interaction (pp. 271-280).
- Light, A., Howland, K., Hamilton, T., & Harley, D. A. (2017). The meaning of place in supporting sociality. In Proceedings of the 2017 Conference on Designing Interactive Systems (pp. 1141-1152).
- Lu, X., & Yao, J. (2010). The Influence of Internet Interpersonal Communication to Relationship and Loneliness of College Students. In 2010 International Conference on Web Information Systems and Mining (Vol. 2, pp. 386-390). IEEE.
- Lou, C., Zhao, J., Li, X., Wei, H., Zhang, Y., & Zhao, H. (2019). Pet Robot Emotional Interaction for Urban Autism. In Proceedings of the 2019 2nd International Conference on Intelligent Science and Technology (pp. 1-6).
- Lubben, J. (2017). Addressing social isolation as a potent killer!. *Public Policy & Aging Report*, 27(4), 136-138.
- Marangoni, C., & Ickes, W. (1989). Loneliness: A theoretical review with implications for measurement. *Journal of Social and Personal Relationships*, 6(1), 93-128.
- Martinez, A., Ortiz, V., Estrada, H., & Gonzalez, M. (2017). A predictive model for automatic detection of social isolation in older adults. In 2017 International Conference on Intelligent Environments (IE) (pp. 68-75). IEEE.
- Matthews, T., Danese, A., Wertz, J., Odgers, C. L., Ambler, A., Moffitt, T. E., & Arseneault, L. (2016). Social isolation, loneliness and depression in young adulthood: a behavioural genetic analysis. *Social psychiatry and psychiatric epidemiology*, 51(3), 339-348.
- Mulvenna, M., Zheng, H., Bond, R., McAllister, P., Wang, H., & Riestra, R. (2017). Participatory design-based requirements elicitation involving people living with dementia towards a home-based platform to monitor emotional wellbeing. In 2017 IEEE International Conference on Bioinformatics and Biomedicine (BIBM) (pp. 2026-2030). IEEE.
- Munn, Z., Peters, M. D., Stern, C., Tufanaru, C., McArthur, A., & Aromataris, E. (2018). Systematic review or scoping review? Guidance for authors when choosing between a systematic or scoping review approach. *BMC medical research methodology*, 18(1), 1-7.
- Noguchi, Y., Kamide, H., & Tanaka, F. (2018). Effects on the self-disclosure of elderly people by using a robot which intermediates remote communication. In 2018 27th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN) (pp. 612-617). IEEE.
- ONS (2018) Loneliness [Online] available at: <https://bit.ly/3zd10ZL> [Accessed 15 May 2021]
- Pedell, S., Vetere, F., Kulik, L., Ozanne, E., & Gruner, A. (2010). Social isolation of older people: the role of domestic technologies. In Proceedings of the 22nd Conference of the Computer-Human Interaction Special Interest Group of Australia on Computer-Human Interaction (pp. 164-167).
- Perlman, D., & Peplau, L. A. (1981). Toward a social psychology of loneliness. *Personal relationships*, 3, 31-56.
- Petersen, J., Austin, D., Kaye, J. A., Pavel, M., & Hayes, T. L. (2013). Unobtrusive in-home detection of time spent out-of-home with applications to loneliness and physical activity. *IEEE journal of biomedical and health informatics*, 18(5), 1590-1596.
- Pulekar, G., & Agu, E. (2016). Autonomously sensing loneliness and its interactions with personality traits using smartphones. In 2016 IEEE healthcare innovation point-of-care technologies conference (HI-POCT) (pp. 134-137). IEEE.
- Rabani, S. T., Khan, Q. R., & Khanday, A. M. U. D. (2020). Multi-Class Suicide Risk Prediction on Twitter Using Machine Learning Techniques. In 2020 2nd International Conference on Advances in Computing, Communication Control and Networking (ICACCCN) (pp. 128-134). IEEE.
- Ring, L., Barry, B., Totzke, K., & Bickmore, T. (2013). Addressing loneliness and isolation in older adults: Proactive affective agents provide better support. In 2013 Humaine Association conference on affective computing and intelligent interaction (pp. 61-66). IEEE.
- Russell, D. W. (1996). UCLA Loneliness Scale (Version 3): Reliability, validity, and factor structure. *Journal of personality assessment*, 66(1), 20-40.
- Russell, D., Cutrona, C. E., Rose, J., & Yurko, K. (1984). Social and emotional loneliness: an examination of Weiss's typology of loneliness. *Journal of personality and social psychology*, 46(6), 1313.
- Scalise, J. J., Ginter, E. J., & Gerstein, L. H. (1984). Multidimensional loneliness measure: the loneliness rating scale (LRS). *Journal of Personality Assessment*, 48(5), 525-530.
- Schmidt, N., & Sermat, V. (1983). Measuring loneliness in different relationships. *Journal of personality and social psychology*, 44(5), 1038.
- Senese, V. P., Nasti, C., Mottola, F., Sergi, I., & Gnisci, A. (2020, September). Validation and measurement

- invariance across gender and age of the Italian Interpersonal Acceptance-Rejection Loneliness Scale. In 2020 11th IEEE International Conference on Cognitive Infocommunications (CogInfoCom) (pp. 000289-000294). IEEE
- Shah, S. G. S., Nogueras, D., Van Woerden, H., & Kiparoglou, V. (2019). Effectiveness of digital technology interventions to reduce loneliness in adults: a protocol for a systematic review and meta-analysis. *BMJ open*, 9(9), e032455.
- Stephoe, A., Shankar, A., Demakakos, P., & Wardle, J. (2013). Social isolation, loneliness, and all-cause mortality in older men and women. *Proceedings of the National Academy of Sciences*, 110(15), 5797-5801.
- Taylor, S. H., Hutson, J. A., & Alicea, T. R. (2017). Social consequences of Grindr use: Extending the internet-enhanced self-disclosure hypothesis. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (pp. 6645-6657).
- Waterworth, J. A., Ballesteros, S., & Peter, C. (2009). User-sensitive home-based systems for successful ageing. In *2009 2nd Conference on Human System Interactions* (pp. 542-545). IEEE.
- Weil, S. (1997). *Gravity and grace*. U of Nebraska Press
- Weinert, C., Maier, C., Laumer, S., & Weitzel, T. (2014). Does teleworking negatively influence IT professionals? An empirical analysis of IT personnel's telework-enabled stress. In *Proceedings of the 52nd ACM conference on Computers and people research* (pp. 139-147).
- Weiss, R. (1975). *Loneliness: The experience of emotional and social isolation*. MIT press.
- Wu, Y., Yuan, J., You, Q., & Luo, J. (2016). The effect of pets on happiness: A data-driven approach via large-scale social media. In *2016 IEEE International Conference on Big Data (Big Data)* (pp. 1889-1894). IEEE.
- Xu, D., Qian, L., Wang, Y., Wang, M., Shen, C., Zhang, T., & Zhang, J. (2015). Understanding the dynamic relationships among interpersonal personality characteristics, loneliness, and smart-phone use: evidence from experience sampling. In *2015 International Conference on Computer Science and Mechanical Automation (CSMA)* (pp. 19-24). IEEE.
- Yang, H., & Bath, P. A. (2018). Prediction of Loneliness in Older People. In *Proceedings of the 2nd International Conference on Medical and Health Informatics* (pp. 165-172).
- Yoshida, M., Kleisarchaki, S., Gtirgen, L., & Nishi, H. (2018). Indoor occupancy estimation via location-aware HMM: An IoT approach. In *2018 IEEE 19th International Symposium on "A World of Wireless, Mobile and Multimedia Networks"(WoWMoM)* (pp. 14-19). IEEE.
- Zadeh, P. M., Khani, S., Pfaff, K., & Samet, S. (2020). A computational model and algorithm to identify social isolation in elderly population. In *2020 IEEE Symposium on Computers and Communications (ISCC)* (pp. 1-6). IEEE.
- Zhang, M. (2010). Exploring adolescent peer relationships online and offline: an empirical and social network analysis. In *2009 WRI International Conference on Communications and Mobile Computing (Vol. 3, pp. 268-272)*. IEEE.
- Zhou, Z., Sun, X., Chen, X., Fan, C., & Pan, Q. (2009). The Relation between Different Constructs in Middle Childhood Peer Interaction and Loneliness: A Mediational Model. In *2009 3rd International Conference on Bioinformatics and Biomedical Engineering* (pp. 1-4). IEEE.
- Zhou, Q., Li, J., Tang, Y., & Wang, H. (2020). Discovering the Lonely Among the Students with Weighted Graph Neural Networks. In *2020 IEEE 32nd International Conference on Tools with Artificial Intelligence (ICTAI)* (pp. 474-481). IEEE.