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Use of Geofencing Interventions in Population Health Research: A Systematic Scoping Review

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Key Points

Question

What geofencing interventions have been implemented in population health research?

Findings

The majority of the 9 studies included in this systematic scoping review were published in the five years preceding the search (89%). Geofences in most studies (n=5) were fixed and programmed in the mobile application carried by participants without their input. Intervention delivery of geofencing interventions were classified as direct or indirect with five studies (56%) being found to have utilized direct interventions.

Meaning

This review found geofencing to be an emerging technology that is an acceptable and feasible intervention.

Abstract

Importance

Technological advancements that utilize global positioning system (GPS), such as geofencing, provide the opportunity to examine place-based context in population health research. However, systematic review of the use of geofencing intervention research is lacking.

Objectives

To systematically identify, assess, and synthesize the existing evidence on geofencing intervention design, acceptability, feasibility, and/or impact.

Evidence Review

Searches were conducted in PubMed, CINAHL, EMBASE Web of Science, Cochrane, and PsychINFO for articles in English published by December 31st, 2021. This systematic scoping review examined existing literature and excluded articles that met the following criteria: 1) a component or combination of global positioning system (GPS), geographic information system (GIS), or ecological momentary assessment (EMA) was utilized without delivery of an intervention; 2) did not include a health or health-related outcome from the geofencing intervention; or 3) was not a peer-reviewed study. Several researchers independently reviewed all abstracts and full-text articles prior to their final inclusion.

Findings

Using the search strategy in six databases, a total of 2171 articles were found. Nine studies were included. The majority were published in five years preceding the search (89%). Geofences in

most studies (n=5) were fixed and programmed in the mobile application carried by participants without their input. Mechanisms of geofencing interventions were classified as direct or indirect with five studies (56%) being found to have utilized direct interventions. Of note, there was not a consistent health outcome (from smoking to problematic alcohol use) across the five studies that utilized an direct geofencing intervention and four studies utilized a behavioral mechanism in their geofencing intervention.

Conclusions and Relevance

This review found geofencing to be an emerging technology that is an acceptable and feasible intervention. Moreover, geofencing interventions have been applied to various populations and health outcomes. However, future studies should be specific about the rationale for the type of locations that are geofenced and the user input. Moreover, attention to the mechanisms of actions will enable the field to understand not only whether geofencing is an appropriate and effective intervention but why it works to achieve the outcomes we observe.

Strengths and Limitations

- This scoping review focused on hypothesized mechanisms of action.
- The number of published studies that met criteria were limited and did not assess impact of the intervention.

Introduction

Population health outcomes and health disparities result from multi-level factors beyond the individual. For example, poverty can lead to a lack of access to healthy food[1] and medical care[2]; unstable housing can lead to inability to adhere to medications [3] and exposures to unhealthy environments[4]; homophobia and racism leads to stigma and discrimination, and mistrust and avoidance of medical systems.[5-7]

Often in behavioral research, theories or frameworks do not consider the place-based context of behavior despite literature on the consistent and enduring impact of places such as neighborhoods and communities on population health outcomes and disparities.[8-10] Place-based context can be conceptualized as both geographic areas defined by boundaries or as socially constructed out of symbolic meanings *and* social relations.[11,12] In both cases, place-based context operates to perpetuate hierarchical social structures, facilitate and constrain resources, and protect or hinder health. Moreover, place-based context may facilitate specific health-related interactions such as drug or alcohol use, experiences of violence, or engagement in healthcare. Yet behavioral interventions often conceptualize place-based context as static (e.g., place of risky sex) and do not consider how place-based contexts vary over time. Real-time geospatial methods, including the use of global positioning system (GPS) technology, are the cutting-edge, best-suited methods to overcome limitations of most neighborhoods and other environments health research because they better capture place-based contexts corresponding to individuals' lived experiences, referred to as "activity space".[14-13]

There are numerous types of GPS-based methods that collect data from individuals and in some cases deliver intervention content. For example, ecological momentary assessment (EMA) has been shown to be an acceptable method of data collection.[14] Ecological Momentary

Interventions (EMI) allow researchers to deliver intervention content through mobile devices.[15] Just-in-time adaptive interventions (JITAI) attempt to address the changing needs of an individua where the intervention algorithm is programmed to determine if and what intervention content should be delivered to participants at set times throughout the day, whenever a participant requests one, or based on the participant's current state (e.g., stress) or environmental changes (e.g., weather).[16-17] Finally, geofences are virtual boundaries drawn around a location and allow for monitoring and messaging when individuals enter or exits the geofenced parameter.[18] Geofencing interventions are a subset of JITAI where there is continuous monitoring of the participant's location using GPS and delivery of an intervention based on a spatial context trigger.

Reviews of JITAI and EMI show the promising potential of this evolving technology[19-21], yet, such reviews are noted to lack the inclusion of geofencing, representing a major gap in the literature. This gap is vital to address as geofencing has the capability to address an array of different health issues ranging from tobacco cessation to HIV medication adherence. The lack of a clear and systematic understanding of the scope of geofencing interventions undermines its potential to impact population health. The purpose of this systematic scoping review is to describe of the state of the evidence on geofencing intervention design, acceptability, feasibility, and impact. In addition, we examine what behavioral mechanisms were targeted across the interventions assessed, as discussed below.

Conceptualizing mechanisms of action

Another limitation in the literature of EMA and JITAI interventions is the lack of attention to specific mechanisms of action that operate to achieve outcomes.[22] Therefore, we sought to

develop a framework based on several complementary theories and frameworks (e.g., Turan's HIV Stigma Framework and Social Cognitive Theory[23-25]) to evaluate geofencing interventions included in this review. The framework posits three key mechanisms operate for place-based context to influence health outcomes (Figure 1). Each mechanism has both a protective and risk dimension. The Cognitive mechanism includes cognitive processes such as sense of control, knowledge, attitudes, self-efficacy, maladaptive thoughts, risk perceptions and internalized stigma.[26-31] The Behavioral mechanism refers to both protective behaviors such as adaptive coping as well as risky behaviors such substance use, condomless sex and non-adherence to medication and care.[32-34 35] The Social mechanism refers to interactions with others in the personal social networks and broader community such as emotional or instrumental support or enacted stigma and conflict which have been shown to exacerbate or mitigate health outcomes.[36-38] The framework can be applied to multiple spatial scales from a micro-level (e.g. a room in one's residence) to community-level (e.g. a neighborhood activity space or census tract) to macro (e.g. state, region).

[Figure 1 here]

Methods

This systematic review was conducted in accordance with the 2018 PRISMA Extension for Scoping Reviews checklist.[39]

Patient and public involvement

No patient involved.

Inclusion criteria

Articles were only included if they included if geofencing was utilized as a mechanism for intervention delivery. Articles were excluded if 1) a component or combination of GPS, geographic information system (GIS), or ecological momentary assessment (EMA) was utilized without delivery of an intervention; 2) did not include a health or health-related outcome from the geofencing intervention; or 3) was not a peer-reviewed study.

Search strategy

Authors first met to develop the list of potential search terms and refined after initial searchers were conducted. Then searches were conducted in PubMed, CINAHL, EMBASE Web of Science, Cochrane, and PsychINFO for articles published through the end of 2021 (Appendix 1). Search terms were for broad concepts regarding mobile delivery of a geofencing intervention: "Geographic Information Systems"; "Georeferencing"; "Global Positioning System"; or "Geofenc*" combined with "Smartphone" or "Mobile Applications." The search was conducted on 12/1/2022 and was not registered. A protocol was not prepared.

Study selection

Screening of article titles and abstracts was conducted with two reviewers (SS, CV) in maximize scrutiny of all records. Each reviewer independently screened all articles identified from the initial search for relevance to the pre-defined inclusion criteria that was highlighted during a training session where it was emphasized that the reviewers should apply a liberal approach. Next, the same two reviewers independently reviewed each of the full texts for inclusion in the data extraction phase. Any disagreements in both phases were adjudicated by a third reviewer

(OH). In all phases reviewers were not blinded to authors, funding, or information regarding publication of all the records.

Data extraction

Two reviewers (OH, KT) extracted data for details of study design, target population, sample size, duration of follow-up, theoretical framework, software or mobile application use, goal, and mechanism of geofenced intervention, and impact of the intervention of outcomes. Place-based mechanisms associated with the intervention included: 1) Behavioral, 2) Social support: Emotional, Instrumental, Informational, and Social monitoring, and 3) Cognitive. Finally, established guidance for reporting health intervention using mobile phone was utilized to evaluate the quality of each article.[40]

Included studies

Using the search strategy in six identified databases, a total of 2,171 articles were found after removing duplicates. 2,039 studies were irrelevant and 132 full text studies were assessed for eligibility (Supplementary Figure 1). Reasons for exclusion of the 122 articles in the full-text phases included the article not being peer reviewed (n=46), a review articles (n=19), was not the correct study design or intervention (n=14), or utilized a combination of GPS, GIS, and or Ecological Momentary Assessment, but was not a geofencing intervention (n=44). Nine studies were included in this scoping review.

Study characteristics

The majority were published in five years preceding the search (89%) (Supplemental Table). Most employed a pre/post study design to assess changes in measured outcome or feasibility and acceptability of the geofencing intervention (78%) with 2 unblinded randomized control trials. Sample sizes ranged from 4-3,443; one study's intervention quantified its reach with the geofencing intervention displaying on 516,073 mobile phones, though these impressions do not represent unique individuals receiving the intervention.[41] Most studies (78%) were conducted in the United States, one in the United Kingdom[42] and one in Spain.[22]

Geofencing methods: User input

Geofences in most studies (n=5) were fixed and programmed in the mobile application without participant input. These included hospital emergency departments[18,43], hospitals where participants worked[44,45], and a specific rural dental clinic[41]. Two studies utilized participants input in determining where to geofence related to smoking[42] or problematic alcohol use[46]. Two studies utilized a mix of fixed and user input. Dorsch et al. utilized user input to geofence locations where foods were consumed or purchased as well as a cloud-based web service to predict when participants entered grocery stores or restaurants. Besoain et al., used a moderated system where participants suggested locations to geofence that were venues for high-risk sexual encounters, but these venues were moderated by the study team and locations could be added or removed.

Intervention content delivery: Direct versus Indirect

Intervention content was delivered in direct or indirect methods. Five studies (56%) sent participants intervention content directly to their phones based on triggering the geofence boundary. These interventions included informing individuals living in a rural area of a dental

clinic[41] or sending behavioral messages regarding problematic alcohol use when near a bar[46], smoking cessation in areas detected as high likelihood of smoking[42], making low-sodium diet choices in grocery stores, restaurants, or at home, or HIV and STI prevention messages when in venues associated with high-risk sexual activity[22]. The remaining 4 studies were categorized as indirect as they collected data when participants triggered geofence boundaries and in some cases delivered content at a later time from when the fence was triggered.

Outcomes of interest

There was not a consistent health outcome across the five studies that utilized a direct intervention. Both studies that utilized a randomized control design showed improved outcomes in the group randomized to geofencing. A-CHESS sent context and place-based messages and included multiple other services such as a phone and data plan, access to a virtual counselor, and other interactive features (Table 1).[46] LowSalt4Life contained features including low sodium options and alternatives at grocery stores or restaurants, and the ability to scan product barcodes to find similar low sodium options. Q Sense intervention participants decreased from 60% of pre-quit smoking days to 39% post-quit. UBESafe intervention reported that all participants were able to trigger a hot zone where sexual contacts often took place and received a place-based prevention message.[22] Finally, Wright et al.,[41] used a pre/post design, and found increases in community knowledge about the dental clinic (p=0.045) and increased number of dental visits post intervention.

Indirect intervention outcomes

Two studies used the geofence to track time working from medical practitioners or surgical residents (Table 1). Owei et al., found the mean number of working hour violations for surgical residents' post-intervention significantly decreased ($p=0.04$) compared to pre-intervention and compared to the previous year ($p<0.01$).[44] Connor et al., showed a significant correlation of early departures from operating room duties following late departures the previous day ($p<0.01$) and better dispersion of working hours ($p=0.002$) compared to the previous year.[45] Two other studies geofenced major hospitals to detect hospitalization of high priority patients. Nguyen et al., found the geofenced mobile application detected 800 unique participants who triggered a geofence, with a predictive value of true hospitalization between 65-78%.[18] Similarly, from a sample size of 21, 4 of the participants activated the alert system for patients with a ventricular assist device to their on-call care team when they triggered an emergency room geofence.[43]

Acceptability measures

Five studies reported data regarding acceptability of the geofencing mobile application in which all participants were positive regarding the value of the intervention. Participants in two studies with indirect intervention found the application useful and described knowledge of being monitored provided a sense of security[43,44]. Additionally, participants in two studies did not have concerns regarding the continuous geolocation tracking for intervention purpose[42,44], but did stress the importance of transparency regarding the use of this data[42]. Finally, in one interactive study, participants contributed to the creation and curation of geofenced hot zones as well as the prevention messages received when hot zones were triggered, accounting for 67% of hot zones created and used by the study[22].

Place-based mechanisms

Four studies utilized a behavioral mechanism in their geofencing intervention.[22,42,46,47] Four studies utilized a social mechanism which included informational support such as existence of a rural dental clinic[41] and availability of menu grocery store items that were low in sodium.[22,41,46,47] Additionally, participants were able to interact with counselors though the application and review their data concerning visiting high-risk locations for further intervention[46] or sharing context specific messages with other users on the application.[22] Finally, five studies utilized a cognitive mechanism that provided the participant a sense of safety, security, or knowing that their information was captured.[45,46] These included reporting to care teams when the participants were hospitalized[18,43], capture of time and effort spent working in a clinical environment[44,45], and participants counselor viewing their location and interacting with their place-based data of proximity and time spent in high-risk areas for binge drinking.[46]

Reporting and quality measures

From the 16-point checklist, all included studies reported on 6 items (Table 1). Position Health[43], Stat![45], and ResQ[44] studies described how the intervention and data collected integrated into an existing health information system and described some data security procedures. A-CHESS[46] and the Wright et al.,[41] intervention conducted some cost assessment regarding the delivery of the intervention or cost to the participant to utilize the participant. Finally, no study reported on compliance of the intervention or data collection mechanism compliance with national guidelines or federal statutes. We did not assess confidence in the body of evidence or risk of bias.

Discussion

The purpose of this review was to describe the use of geofencing as an intervention and mechanisms that were targeted to achieve various health outcomes. We identified only 9 studies that fit criteria and as expected, most publications were relatively recent.

Of the studies included, only one was focused on a sexual and gender minority sample and only one with majority Black, Indigenous People of Color (BIPOC), who experience disparities on a vast number of health outcomes due to social and structural factors such as racism and homophobia.[22] Lack of inclusion of these populations is a significant gap that should be monitored as more studies are conducted. In addition, most studies were in the U.S. (North America) with no studies in developing countries, South America, Africa or Asia, which could represent an important opportunity.

The included studies described a range of user input of the geofenced locations from researcher only selection to user selection. This characteristic of an intervention merits consideration. User selection of geofenced locations may be prone to bias and recall issues.[48] Researcher selected locations may not consider the variability of their sample's place-based contexts and may under count locations that should be geofenced. The hybrid approach has the potential to address both limitations. Future studies using geofencing technology may warrant comparative studies of the user input approaches and be specific about the rationale for the type of locations that are geofenced and the user input of these so that studies can be comparable and be conducted in non-western contexts.

Some of the interventions explicitly identified a theoretical model or foundation, and all the studies described targeting at least one of the mechanisms of action from our proposed framework. The studies in which the geofencing intervention targeted the cognitive mechanism were primarily addressing surveillance of the participants and messages to cue cognitions about

their location. Cueing is a significant component of many effective interventions as they serve as reminders to engage in behaviors of interest.[49-51] Cues can focus on both the protective and risk dimensions of the mechanism. For example, if an individual triggers a geofence of a place they have identified as associated with a sense of control, cues to engage in coping and self-care will be more relevant. Cues in places where stigma is anticipated can also encourage adaptive coping behaviors.

Studies utilizing the behavioral mechanism described very specific behavioral targets such as buying lower sodium food, avoiding places of alcohol use, condom use and smoking cessation. As building self-efficacy is a well-established theoretical construct necessary for behavioral change[23], future studies should include opportunities to watch the desired behaviors be role-modeled and practiced to enhance the efficacy of the geofencing intervention.[52]

Studies that utilized the social mechanism were focused on the provision of both informational and emotional support. One study included a component in which the participants could create messages for other user of the geofencing application. As there are different types of social support (e.g., emotional, appraisal, economic and informational) future studies should be specific and transparent about the types being targeted. With additional geofencing studies, a future review can be conducted using meta-analytic methods to determine the quantitative effectiveness of geofencing interventions in population health research.

Limitations

The search strategy was limited to PubMed, CINAHL, EMBASE Web of Science, Cochrane, and PsychINFO and we acknowledge other publications may not have been captured with these. There was heterogeneity in how studies reported intervention development, theoretical frameworks, and feasibility and acceptability of the intervention. This reduced the ability to

properly assess the extent of behavioral mechanism utilized for the given outcome. Additionally, as geofencing is a new technology, not many peer-reviewed articles have been published and this scoping review chose to exclude conference abstracts.

Conclusions

In conclusion, this systematic scoping review indicates that geofencing is an emerging acceptable and feasible intervention that has been applied to various populations and health outcomes.[22] Attention to the mechanisms of actions will enable the field to understand not only whether geofencing is an appropriate and effective intervention but why it works to achieve the outcomes we observe. There is a need for future research that includes sexual and gender minority and BIPOC populations and populations from non-Western contexts to achieve the Health People Framework objectives given the persistent findings that BIPOC and SGM populations. These studies could address those health outcomes where disparities are stark such as HIV/AIDS, cardiovascular, diabetes, COVID-related and monkeypox. Finally, future research can reveal place-based contexts that have not been considered which can inform resource allocation and targets for health-promoting policies.

Table 1. **Components of mobile health evidence reporting and assessment.**

	Wright et al., 2021	Owei et al., 2021	Gustafson et al., 2014	Nguyen et al., 2017	Naughton et al., 2016	Dorsch et al., 2020	DeFilippis et al., 2017	Connor & Herzig, 2016	Besoain et al., 2020
Infrastructure	■	■	■	■	■	■	■	■	■
Technology platform	■	■	■	■	■	■	■	■	■
Interpretability/Health information systems context		■					■	■	
Intervention delivery	■	■	■	■	■	■	■	■	■
Intervention content	■	■	■	■	■	■	■	■	■
Usability/content testing					■		■	■	■
User feedback		■		■	■		■	■	■
Access of individual participants		■	■	■	■		■	■	■
Cost assessment	■		■						
Adoption inputs/program entry	■	■	■	■	■	■	■	■	■
Limitations for delivery at scale		■		■	■				
Contextual adaptability					■				
Replicability			■			■	■	■	■
Data security							■	■	
Compliance with national guidelines or regulatory statutes									
Fidelity of the intervention	■	■	■	■	■	■	■	■	■

Contributorship statement

All authors conceptualized and contributed to writing this manuscript. Co-first authors Tobin and Heidari led the data abstraction and analysis.

Competing interests

Karin E. Tobin, Omeid Heidari, Connor Volpi, Shereen Sodder and Duston Duncan declare that they have no conflict of interest.

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Data sharing statement

We will consider requests for access to methods or the data used in this study. Template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review are available upon request to the lead author

Human and Animal Rights and Informed Consent

This article does not contain any studies with human or animal studies performed by any of the authors.

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Figure 1. Types of mechanisms of action, protective and risk factors as well as spatial scales in geofencing interventions in population health research.

Mechanisms of Action	**Protective**	**Risk**	Spatial Scales
Cognitive	Sense of control Self-efficacy	Internalized & anticipated stigma Risk perceptions	Room Home Block Neighborhood City County State Region Nation Globe
Behavioral	Adaptive Coping Self-care	Substance use Non-adherence to medication	
Social	Instrumental & Emotional support	Enacted stigma Conflict	

Appendix 1. Detailed search strategy across n=6 databases

PubMed

Concept	Search Terms
Mobile applications	("Smartphone"[Mesh]) OR "Mobile Applications"[Mesh] OR smartphon* [tiab] OR "mobile application*" [tw] OR "mobile app" [tw] OR "mobile apps" [tw] OR "mobile phon*" [tw]
Geofencing	"Geographic Information Systems"[Mesh] OR "Geographic Information System" [tw] OR "Geographical Information System" [tw] OR "Geographical Information Systems" [tw] OR "Georeferencing" [tw] OR "Global Positioning System" [tw] OR "Global Positioning Systems" [tw] OR "Geofenc*" [tw]

Embase

Concept	Search Terms
Mobile applications	'mobile phone'/exp OR 'wireless communication'/exp OR 'mobile application'/exp OR smartphon*:ti,ab,kw OR 'mobile application*':ti,ab,kw OR 'mobile app':ti,ab,kw OR 'mobile apps':ti,ab,kw OR 'mobile phon*':ti,ab,kw
Geofencing	'geographic information system'/exp OR 'global positioning system'/exp OR 'geographic information system':ti,ab,kw OR 'geographical information system':ti,ab,kw OR 'geographical information systems':ti,ab,kw OR 'georeferencing':ti,ab,kw OR 'global positioning system':ti,ab,kw OR 'global positioning systems':ti,ab,kw OR 'geofenc*':ti,ab,kw

CINAHL

Concept	Search Terms
Mobile applications	(MH "Smartphone") OR (MH "Cellular Phone+") OR (MH "Text Messaging+") OR (MH "Mobile Applications") OR smartphon* OR "mobile application*" OR "mobile app" OR "mobile apps" OR "mobile phon*"
Geofencing	(MH "Geographic Information Systems+") OR "Geographic Information System" OR "Geographical Information System" OR "Geographical Information Systems" OR "Georeferencing" OR "Global Positioning System" OR "Global Positioning Systems" OR Geofenc*

Cochrane

Concept	Search Terms
Mobile applications	([mh Smartphone]) OR [mh "Mobile Applications"] OR smartphon*:ti,ab OR ("mobile" NEXT application*):ti,ab,kw OR "mobile app":ti,ab,kw OR "mobile apps":ti,ab,kw OR ("mobile" NEXT phon*):ti,ab,kw

Geofencing	[mh "Geographic Information Systems"] OR "Geographic Information System":ti,ab,kw OR "Geographical Information System":ti,ab,kw OR "Geographical Information Systems":ti,ab,kw OR Georeferencing:ti,ab,kw OR "Global Positioning System":ti,ab,kw OR "Global Positioning Systems":ti,ab,kw OR Geofenc*:ti,ab,kw

Web of Science

Concept	Search Terms
Mobile applications	(ALL=((Smartphone) OR "Mobile Applications" OR smartphon* OR "mobile application*" OR "mobile app" OR "mobile apps" OR "mobile phon*"))
Geofencing	ALL=("Geographic Information Systems" OR "Geographic Information System" OR "Geographical Information System" OR "Geographical Information Systems" OR Georeferencing OR "Global Positioning System" OR "Global Positioning Systems" OR Geofenc*)

APA PsychINFO

Concept	Search Terms
Mobile applications	DE "Smartphones" OR DE "Mobile Applications" OR DE "Smartphone Use" OR DE "Text Messaging" OR DE "Wireless Technologies" OR DE "Mobile Phones" OR smartphon* OR "mobile application*" OR "mobile app" OR "mobile apps" OR "mobile phon*"
Geofencing	"Geographic Information System" OR "Geographical Information System" OR "Geographical Information Systems" OR "Georeferencing" OR "Global Positioning System" OR "Global Positioning Systems" OR Geofenc*

Figure 1. PRISMA diagram of selected studies

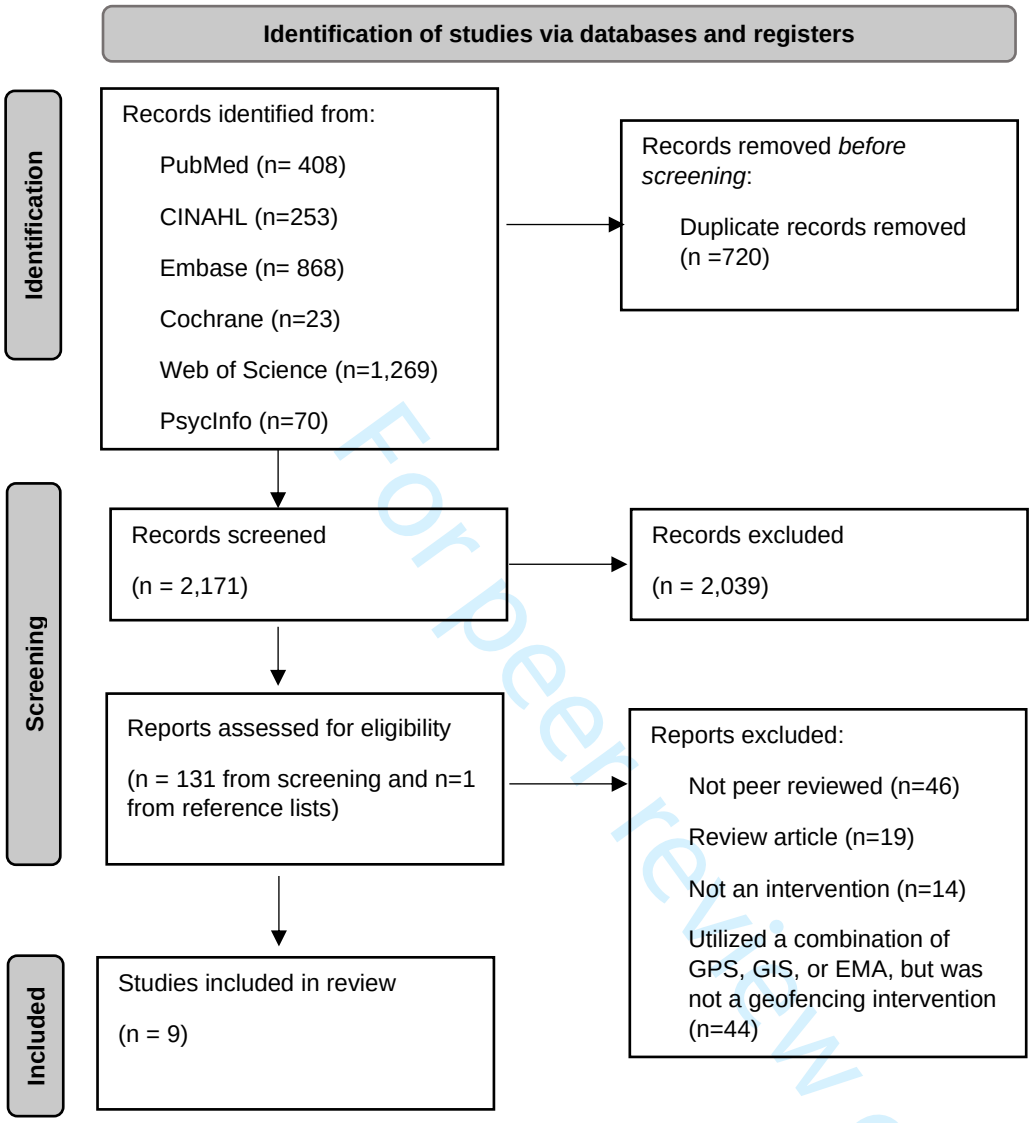

Table 1. **Details of nine studies that met inclusion criteria for the scoping review**

Geofenced intervention name/citation	Study characteristics	Development of geofence	Results	Theory and framework
Wright et al., 2021 Vendor not cited	*Study purpose:* Increase awareness and use of dental services in a rural clinic *Study design:* Pre and post intervention community and outcome assessments *Target population:* Residents of a rural zip code surrounding a dental clinic *Sample size:* 516,073 impressions delivered to individuals crossing the geofence *Duration of follow-up:* Impressions were sent over a 60-day period *Outcome of interest:* Number of impressions displayed to a user, clicks on the banner, click-through rates on the dental website from the banner, and pre/post intervention community knowledge of the dental clinic	*User input:* None *Mechanism of delivery:* Any individual with a smartphone physically located within the boundaries of three zip codes near the dental clinic received a geofence message advertising the dental clinic with webpage information for additional information	Over 60 days, 516,073 impressions were delivered, with 475 individuals clicks on the banner to get website information, and a click through rate of 0.09%. Increases were seen in community knowledge about the clinic (p=0.045) and dental visits by respondent or a family member (p=0.04) post intervention	*Theoretical framework:* Anderson Model of Health Services Use *Behavioral* *Social:* Informational support of an existing service that is place-based *Cognitive*
Owei et al., 2021 ResQ	*Study purpose:* Assess the impact of the ResQ geofencing app on submission rates for duty hours and number of violations reported *Study design:* Mixed methods feasibility and acceptability of the ResQ app. *Target population:* Residents from the General Surgery Residency Program	*User input:* None *Mechanism of delivery:* Geofences were placed around clinical sites where residents worked. The ResQ application was installed on resident's work phones and	The mean number of violations decreased significantly (p=0.04) and work hour submissions did not differ with the intervention (p=0.42). Compared to the previous year, reported violations significantly decreased (p<0.01).	*Theoretical framework:* None listed *Behavioral* *Social* *Cognitive:* Sense of safety in capture

	Sample size: 23 *Duration of follow-up:* 60 days *Outcome of interest:* Comparison of reported and recorded work hours submitted and work hour violations (80 hours per week and continuous hours worked). Additionally, 13 participants participated in semi-structured interviews to understand acceptability and feasibility of ResQ.	recorded work hours based on entering and exiting the geofence.	Participants found the application useful for recording and reporting clinical hours and eased administrative burden.	and reporting of clinical hours
Gustafson et al., 2014 A-CHESS	*Study purpose:* Determine if a smartphone application to support recovery from alcohol use disorders reduced risky drinking days. *Study design:* Unmasked randomized clinical trial *Target population:* People with diagnosed alcohol dependence discharged from residential treatment *Sample size:* 349 *Duration of follow-up:* 8 months *Outcome of interest:* Risky drinking days in the previous 30 days	*User input:* High-risk locations were identified by participants *Mechanism of delivery:* Study team geofenced user identified high-risk locations and sent alerts to the user's smartphone asking if they wanted to be there	Along with the geofenced intervention, A-CHESS was a mobile application that provided monitoring, information, communication, and support services from counselors. Overall the A-CHESS group reported fewer risky drinking days at follow-up (p=0.003)	*Theoretical framework:* Self-determination theory *Behavioral:* Warning messages sent in risky areas *Social:* Informational support with counselors *Cognitive:* Passive and real-time capture of information shared with counselors
Nguyen et al., 2017 Ginger.io	*Study purpose:* Evaluate the use of smartphone-based geofencing for tracking hospitalizations	*User input:* None *Mechanism of delivery:* The app was programmed with all	Remote- The application detected 800 unique participants in a geofenced location with a positive predictive value between 65-	*Theoretical framework:* None listed

	Study design: Remote and in-person arm validation of1 a mobile application that detected hospitalizations and length of hospitalization *Target population:* Remote- participants from the Health eHeart study with a smartphone In-person- Patients scheduled for electrophysiology and cardiac catheterization procedures. *Sample size:* Remote- 3,443; In person- 22 *Duration of follow-up:* Remote- mean of 260 days; In person- Duration of their scheduled procedure *Outcome of interest:* Detection of hospitalization	U.S. hospitals geofenced. A notification was sent to within 1 hour of leaving the hospital vicinity asking participants to confirm if they received medical care	78% based on how hospitalization was confirmed. Most common error in detection was the participant was a medical center employee. In person- Visits were detected in 17/22 with confirmed hospitalization. Mean visit duration was not correlated with actual hospital length of stay.	*Behavioral* *Social* *Cognitive:* Sense of safety in provider knowing your hospitalization status
Naughton et al., 2016 Q Sense	*Study purpose:* Feasibility and acceptability of a mobile application using geofencing to deliver tailored place-based intervention messages *Study design:* Explanatory sequential mixed methods *Target population:* Tobacco smokers willing to set a quit date within 1 month *Sample size:* 15 in quantitative arm and 13 qualitative interviews	*User input*: Geofences based on user habits and reports of smoking locations *Mechanism of delivery:* If a smoker reported smoking in the same proximity, the device created a geofence around that area with a radius of 100m. When a user entered the geofence for greater than 5	User engagement with the application varied from 60% of days pre-quit and 39% post-quit (52% excluding outliers). Geolocation was collected on 97% of smoking reports with high accuracy. A mean of 1.5 geofences were created per participant with 87% having at least one. 5/9 participants eligible to receive a geofenced triggered message received at least one.	*Theoretical framework:* Learning theory and taxonomy of smoking behavior change *Behavioral:* Coping and resilience regarding smoking triggers *Social* *Cognitive*

	Duration of follow-up: Pre-quit period (up to 1 month) and 2 weeks post-quit date *Outcome of interest:* 1) User engagement with app; 2) Assess app's location-sensing accuracy; 3) Feasibility of geofence mechanism; 4) Limitations of everyday use of app	minutes a location-tailored support messaged was triggered	Environmental constraints and forgetfulness were common reasons for forgetting to engage with app. Participants were positive about the value of the geofenced support and had no privacy concerns.	
Dorsch et al., 2020 LowSalt4Life	*Study purpose:* Effectiveness of the LowSalt4Life mobile app on maintaining a low sodium diet and controlling blood pressure *Study design:* Unblinded randomized control trial *Target population:* Adults diagnosed with hypertension and taking antihypertensive medication *Sample size:* 50 randomized *Duration of follow-up:* 8 weeks *Outcome of interest:* Changes in 24-hour dietary recall and sodium intake, urine sodium excretion, blood pressure	*User input:* Mixed. Geofences were created based on user input as well as from a predictive service when a participant entered a grocery store, restaurant, or home. *Mechanism of delivery:* Contextual adaptive messages were sent to participant's phones when entering a geofence, with messages linked to content in the mobile application	There was a significant decrease in sodium excretion (p=0.03) and decrease in sodium intake via 24 hour dietary recall (p=0.01) and in the App group vs no App groups. Blood pressure decreased by 1.7 mmHg in the App group compared to 0.7 in the no App, but the change was not significant (p=0.12).	*Theoretical framework:* Theory of Planned Behavior *Behavioral:* Dietary messages sent when participant is in areas where they would purchase/consume food *Social:* Informational support regarding which products and food choices had lower sodium in context of place *Cognitive*
DeFilippis et al., 2017 Position Health	*Study purpose:* Determine the feasibility of patients with ventricular assist devices care engagement with and feasibility of a geofencing notification system.	*User input:* None *Mechanism of delivery:* Geofences were drawn around	The system was active on 4 occasions, each of which the participant confirmed they were at or near the hospital but were not seeking care. 1	*Theoretical framework:* None listed *Behavioral*

	Study design: Feasibility study with quantitative and qualitative measures *Target population:* Adults with a ventricular assist device (VAD) *Sample size:* 21 *Duration of follow-up:* 6 months *Outcome of interest:* Proper detection of emergency department utilization by participant and satisfaction with mobile application.	emergency departments (ED) across the U.S. Once the application detected that a participant approached an ED, a prompt was sent to their phone to confirm if they were seeking care at that hospital. If yes, another prompt asked the participant to confirm if the app could notify their VAD healthcare team. If 'yes' to both, a notification was sent to the covering provider's pager with participant name and contact.	patient reported seeking ED care but did not receive a ping. Most patients responded favorable to their impression of the application stating that it "gave them peace of mind."	*Social* *Cognitive*: Sense of safety to participants that emergency room and hospitalizations could alert their VAD provider regarding the need to coordinate care
Connor & Herzig, 2016 Stat!	*Study purpose:* Determine the feasibility and acceptability of a mobile application that allow automatic capture of work hours without manual employee input *Study design:* Feasibility study *Target population:* Anesthesia providers in a private practice group *Sample size:* 198	*User input:* None *Mechanism of delivery:* Geofences were drawn around hospitals where the anesthesia group provided services. When the provider enters a geofence, their time at the facility is continuously	Use of the geofencing application showed a significant correlation of early departures following late departures the previous day ($p<0.01$ in 73 of 91 occasions), and better dispersion of working hours ($p=0.002$) compared to the previous year.	*Theoretical framework:* None listed *Behavioral* *Social* *Cognitive:* Sense of security regarding equitable distribution of work

	Duration of follow-up: 12 months *Outcome of interest:* Equitable workload distribution, employee acceptance and uptake, and reduced dispersion of the amount of overtime worked by staff	checked and reported to a central server. Reports were then used to inform future clinical responsibilities and overtime worked	Acceptance of the mobile application was slow to start but >95% in less than 1 year of roll out	based on geofenced data and capture of time working for billing purposes
Besoain et al., 2020 UBESafe	*Study purpose:* Prevent sexually transmitted infections (STIs) by sending preventive measures in risky situations *Study design:* Development and feasibility *Target population:* Men who have sex with men *Sample size:* Development-5; Feasibility- 4 *Duration of follow-up:* Development- 2 weeks; Feasibility- 1 month *Outcome of interest:* Development- functional testing to receive user feedback; Feasibility- try the UBESAFE system with all its functionalities	*User input:* Mixed. Hot zones were created by a system administrator and with input from users *Mechanism of delivery:* Geofenced hot zones are areas demines with a high probability for intercourse. When users enter a hot zone, a contextual message to prevent HIV and STIs, and promote testing	All users triggered a geofenced hotzone during the development phase, though this was not quantified further. Hot zones were seen as a necessary component from those testing in the development phase. In the feasibility phase, users tested and rated prevention messages as well as adding their own. Users also contributed to hot zones and tested existing ones, contributing 65% of hot zones in the application at the end of the study.	*Theoretical framework:* Elaboration likelihood model *Behavioral:* Contextual messages for sexual risk reduction sent in hot spots for high-risk intercourse *Social:* Gamification of preventive messages and interaction with others using the application *Cognitive*

PRISMA 2020 Checklist

Section and Topic	Item #	Checklist item	Location where item is reported
TITLE			
Title	1	Identify the report as a systematic review.	✓ title
ABSTRACT			
Abstract	2	See the PRISMA 2020 for Abstracts checklist.	
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	✓ Lines 122-130, 133-134
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	✓ Lines 123-130, 134-137
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	✓ Lines 167-171
Information sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	✓ Lines 174-179 ✓ Lines 179-180
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	✓ Lines 174-179
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	✓ Lines 181-189
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	✓Lines 182-183 ✓Lines 191-198
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	✓Lines 194-196
	10b	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	✓Lines 220-221, types of geofencing methods; 231-232, intervention content delivery; line 242, outcomes of interest; lines 256, indirect int. outcomes; line

PRISMA 2020 Checklist

Section and Topic	Item #	Checklist item	Location where item is reported
			269, acceptability measures; line 280, place-based mechanisms; line 293, reporting & quality measures
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	✓ Lines 182-189
Effect measures	12	Specify for each outcome the effect measure(s) (e.g. risk ratio, mean difference) used in the synthesis or presentation of results.	NA
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g. tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).	✓ lines 201-207
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	NA
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	NA
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g. subgroup analysis, meta-regression).	NA
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	NA
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	✓ Lines 295-301
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	✓Line 301
RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	✓Lines 201-307
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	✓Lines 203-206
Study characteristics	17	Cite each included study and present its characteristics.	✓ Table, page 18
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	✓Line 301
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables or plots.	✓Apprendix 1
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.	✓Line 221-292
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g. confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the	NA

PRISMA 2020 Checklist

Section and Topic	Item #	Checklist item	Location where item is reported
		effect.	
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	NA
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	NA
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	Lines 346-350; Line 301
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	Lines 346-350; Line 301
DISCUSSION			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	
	23b	Discuss any limitations of the evidence included in the review.	Lines 344-349
	23c	Discuss any limitations of the review processes used.	346-347
	23d	Discuss implications of the results for practice, policy, and future research.	Lines 352-362
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	Line 180
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	Line 180
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	NA
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	✓Page 19
Competing interests	26	Declare any competing interests of review authors.	✓ Page 19
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	Data sharing statement page 19

From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71
For more information, visit: http://www.prisma-statement.org/

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Use of Geofencing Interventions in Population Health Research: A Scoping Review

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Abstract

Objectives: Technological advancements that utilize global positioning system (GPS), such as geofencing, provide the opportunity to examine place-based context in population health research. To systematically identify, assess, and synthesize the existing evidence on geofencing intervention design, acceptability, feasibility, and/or impact.

Design: A scoping review using the PRISMA-ScR guidance for reporting.

Data Sources: PubMed, CINAHL, EMBASE Web of Science, Cochrane, and PsychINFO for articles in English published by December 31st, 2021.

Eligibility Criteria: Articles were included if geofencing was utilized as a mechanism for intervention delivery. Exclusion criteria: 1) a component or combination of GPS, geographic information system (GIS), or ecological momentary assessment (EMA) was utilized without delivery of an intervention; 2) did not include a health or health-related outcome from the geofencing intervention; or 3) was not a peer-reviewed study.

Data extraction and synthesis: Several researchers independently reviewed all abstracts and full-text articles for final inclusion.

Results: A total of 2171 articles were found. Nine studies were included. The majority were published in five years preceding the search (89%). Geofences in most studies (n=5) were fixed and programmed in the mobile application carried by participants without their input. Mechanisms of geofencing interventions were classified as direct or indirect with five studies (56%) utilized direct interventions. There was a variety of health outcomes (from smoking to problematic alcohol use) across the five studies that utilized an direct geofencing intervention.

Conclusions: This review found geofencing to be an emerging technology that is an acceptable and feasible intervention applied to various populations and health outcomes. Future studies

should specify the rationale for the locations that are geofenced and user input. Moreover, attention to mechanisms of actions will enable scientists to understand not only whether geofencing is an appropriate and effective intervention but why it works to achieve the outcomes we observe.

Strengths and Limitations

- The scoping review was comprehensive utilizing six rigorous databases.
- The review used the Preferred Reporting Items for Systematic Reviews and Meta-analyses extension for Scoping Reviews (PRISMA-ScR) checklist.
- The review only included studies conducted in the United States which has limited generalizability to other international settings.
- The review was conducted through the published literature through 2021 and therefore does not include more recent publications.

Introduction

Population health outcomes and health disparities result from multi-level factors beyond the individual. For example, poverty can lead to a lack of access to healthy food[1] and medical care[2]; unstable housing can lead to inability to adhere to medications [3] and exposures to unhealthy environments[4]; homophobia and racism leads to stigma and discrimination, and mistrust and avoidance of medical systems.[5-7]

Often in behavioral research, theories or frameworks do not consider the place-based context of behavior despite literature on the consistent and enduring impact of places such as neighborhoods and communities on population health outcomes and disparities.[8-10] Place-based context can be conceptualized as both geographic areas defined by boundaries or as socially constructed out of symbolic meanings *and* social relations.[11,12] In both cases, place-based context operates to perpetuate hierarchical social structures, facilitate and constrain resources, and protect or hinder health. Moreover, place-based context may facilitate specific health-related interactions such as drug or alcohol use, experiences of violence, or engagement in healthcare. Yet behavioral interventions often conceptualize place-based context as static (e.g., place of risky sex) and do not consider how place-based contexts vary over time. Real-time geospatial methods, including the use of global positioning system (GPS) technology, are the cutting-edge, best-suited methods to overcome limitations of most neighborhoods and other environments health research because they better capture place-based contexts corresponding to individuals' lived experiences, referred to as "activity space".[14-13]

There are numerous types of GPS-based methods that collect data from individuals and in some cases deliver intervention content. For example, ecological momentary assessment (EMA) has been shown to be an acceptable method of data collection.[14] Ecological Momentary

Interventions (EMI) allow researchers to deliver intervention content through mobile devices.[15] Just-in-time adaptive interventions (JITAI) attempt to address the changing needs of an individual where the intervention algorithm is programmed to determine if and what intervention content should be delivered to participants at set times throughout the day, whenever a participant requests one, or based on the participant's current state (e.g., stress) or environmental changes (e.g., weather).[16-17] Finally, geofences are virtual boundaries drawn around a location and allow for monitoring and messaging when individuals enter or exits the geofenced parameter.[18] Geofencing interventions are a subset of JITAI where there is continuous monitoring of the participant's location using GPS and delivery of an intervention such as text messages or links to health information or information about health services that are in the area based on a spatial context trigger. A geofence involves creating virtual predefined set of boundaries or "fences" around a geographic location, including using GPS technology. Geofencing methodology can be used in public health research – both in observational and intervention studies. Thus, geofencing can be a valuable tool in intervention research, enabling researchers to study and implement interventions in specific geographic areas. For example, geofencing allows researchers to precisely target specific areas for intervention. In addition, geofencing allows researchers to send location-based notifications (an intervention) to participants, including on their mobile devices. One example of this in the public health setting is the use of geofencing to monitor movements of individuals who tested positive for COVID-19 virus.[19]

Reviews of JITAI and EMI show the promising potential of this evolving technology[20-22], yet, such reviews are noted to lack the inclusion of geofencing, representing a major gap in the literature. This gap is vital to address as geofencing has the capability to address an array of

different health issues ranging from tobacco cessation to HIV medication adherence. The lack of a clear and systematic understanding of the scope of geofencing interventions undermines its potential to impact population health. The purpose of this scoping review is to describe of the state of the evidence on geofencing intervention design, acceptability, feasibility, and impact. In addition, we examine what behavioral mechanisms were targeted across the interventions assessed, as discussed below.

Conceptualizing mechanisms of action

Another limitation in the literature of EMA and JITAI interventions is the lack of attention to specific mechanisms of action that operate to achieve outcomes.[23] Therefore, we sought to develop a framework based on several complementary theories and frameworks (e.g., Turan's HIV Stigma Framework and Social Cognitive Theory[24-26]) to evaluate geofencing interventions included in this review. The framework posits three key mechanisms operate for place-based context to influence health outcomes (Figure 1). Each mechanism has both a protective and risk dimension. The Cognitive mechanism includes cognitive processes such as sense of control, knowledge, attitudes, self-efficacy, maladaptive thoughts, risk perceptions and internalized stigma.[27-32] The Behavioral mechanism refers to both protective behaviors such as adaptive coping as well as risky behaviors such substance use, condomless sex and non-adherence to medication and care.[33-35 36] The Social mechanism refers to interactions with others in the personal social networks and broader community such as emotional or instrumental support or enacted stigma and conflict which have been shown to exacerbate or mitigate health outcomes.[37-39] The framework can be applied to multiple spatial scales from a micro-level (e.g. a room in

one's residence) to community-level (e.g. a neighborhood activity space or census tract) to macro (e.g. state, region).

[Figure 1 here]

Methods

This systematic review was conducted in accordance with the 2018 PRISMA Extension for Scoping Reviews checklist.[40]

Inclusion criteria

Articles were only included if they included if geofencing was utilized as a mechanism for intervention delivery. Articles were excluded if 1) a component or combination of GPS, geographic information system (GIS), or ecological momentary assessment (EMA) was utilized without delivery of an intervention; 2) did not include a health or health-related outcome from the geofencing intervention; or 3) was not a peer-reviewed study.

Search strategy

Authors first met to develop the list of potential search terms and refined after initial searchers were conducted. Then searches were conducted in PubMed, CINAHL, EMBASE Web of Science, Cochrane, and PsychINFO for articles published through the end of 2021 (Appendix 1). Search terms were for broad concepts regarding mobile delivery of a geofencing intervention: "Geographic Information Systems"; "Georeferencing"; "Global Positioning System"; or "Geofenc*" combined with "Smartphone" or "Mobile Applications." The search was conducted on 12/1/2022 and was not registered. A protocol was not prepared.

Study selection

Screening of article titles and abstracts was conducted with two reviewers (SS, CV) in maximize scrutiny of all records. Each reviewer independently screened all articles identified from the initial search for relevance to the pre-defined inclusion criteria that was highlighted during a training session where it was emphasized that the reviewers should apply a liberal approach. Next, the same two reviewers independently reviewed each of the full texts for inclusion in the data extraction phase. Any disagreements in both phases were adjudicated by a third reviewer (OH). In all phases reviewers were not blinded to authors, funding, or information regarding publication of all the records.

Data extraction

Two reviewers (OH, KT) extracted data for details of study design, target population, sample size, duration of follow-up, theoretical framework, software or mobile application use, goal, and mechanism of geofenced intervention, and impact of the intervention of outcomes. Place-based mechanisms associated with the intervention included: 1) Behavioral, 2) Social support: Emotional, Instrumental, Informational, and Social monitoring, and 3) Cognitive. Finally, established guidance for reporting health intervention using mobile phone was utilized to evaluate the quality of each article.[41]

Patient and Public Involvement

None

Results

Included studies

Using the search strategy in six identified databases, a total of 2,171 articles were found after removing duplicates. 2,039 (94%) studies were irrelevant and 132 (6%) full text studies were assessed for eligibility (Supplementary Table 1). Reasons for exclusion of the 123 articles in the full-text phases included the article not being peer reviewed (n=46, 37%), a review articles (n=19, 16%), was not the correct study design or intervention (n=14, 11%), or utilized a combination of GPS, GIS, and or Ecological Momentary Assessment, but was not a geofencing intervention (n=44, 36%). Nine studies were included in this scoping review.

Study characteristics

The majority were published in five years preceding the search (89%) (Supplemental Table 1). Most employed a pre/post study design to assess changes in measured outcome or feasibility and acceptability of the geofencing intervention (78%) with 2 unblinded randomized control trials. Sample sizes ranged from 4 to 3,443; one study's intervention quantified its reach with the geofencing intervention displaying on 516,073 mobile phones, though these impressions do not represent unique individuals receiving the intervention.[42] Most studies (78%) were conducted in the United States, one in the United Kingdom[43] and one in Spain.[23]

A description of studies, including the names of the mobile applications used, study design and characteristics, and place-based mechanisms are detailed in Supplemental Table 1.

The design of the geofencing interventions varied based on user input and content delivery.

Geofencing methods: User input

Geofences in most studies (n=5) were fixed and programmed in the mobile application without participant input. These included hospital emergency departments[18,44], hospitals where participants worked[45,46], and a specific rural dental clinic[42]. Two studies utilized participants

input in determining where to geofence related to smoking[43] or problematic alcohol use[47]. Two studies utilized a mix of fixed and user input. Dorsch et al. utilized user input to geofence locations where foods were consumed or purchased as well as a cloud-based web service to predict when participants entered grocery stores or restaurants. Besoain et al., used a moderated system where participants suggested locations to geofence that were venues for high-risk sexual encounters, but these venues were moderated by the study team and locations could be added or removed.

Intervention content delivery: Direct versus Indirect

Intervention content was delivered in direct or indirect methods. Five studies (56%) sent participants intervention content directly to their phones based on triggering the geofence boundary. These interventions included informing individuals living in a rural area of a dental clinic[42] or sending behavioral messages regarding problematic alcohol use when near a bar[47], smoking cessation in areas detected as high likelihood of smoking[43], making low-sodium diet choices in grocery stores, restaurants, or at home, or HIV and STI prevention messages when in venues associated with high-risk sexual activity[23]. The remaining 4 studies were categorized as indirect as they collected data when participants triggered geofence boundaries and in some cases delivered content at a later time from when the fence was triggered.

Impact of the interventions

There was not a consistent health outcome across the five studies that utilized a direct intervention. Both studies that utilized a randomized control design showed improved outcomes in the group randomized to geofencing. A-CHESS sent context and place-based messages and

included multiple other services such as a phone and data plan, access to a virtual counselor, and other interactive features (Table 1).[47] LowSalt4Life contained features including low sodium options and alternatives at grocery stores or restaurants, and the ability to scan product barcodes to find similar low sodium options. Q Sense intervention participants decreased from 60% of pre-quit smoking days to 39% post-quit. UBESafe intervention reported that all participants were able to trigger a hot zone where sexual contacts often took place and received a place-based prevention message.[22] Finally, Wright et al.,[41] used a pre/post design, and found increases in community knowledge about the dental clinic (p=0.045) and increased number of dental visits post intervention.

Indirect intervention outcomes

Two studies used the geofence to track time working from medical practitioners or surgical residents (Supplemental Table 1). Owei et al., found the mean number of working hour violations for surgical residents' post-intervention significantly decreased (p=0.04) compared to pre-intervention and compared to the previous year (p<0.01).[44] Connor et al., showed a significant correlation of early departures from operating room duties following late departures the previous day (p<0.01) and better dispersion of working hours (p=0.002) compared to the previous year.[45] Two other studies geofenced major hospitals to detect hospitalization of high priority patients. Nguyen et al., found the geofenced mobile application detected 800 unique participants who triggered a geofence, with a predictive value of true hospitalization between 65-78%.[18] Similarly, from a sample size of 21, 4 of the participants activated the alert system for patients with a ventricular assist device to their on-call care team when they triggered an emergency room geofence.[44]

Acceptability measures

Five studies reported data regarding acceptability of the geofencing mobile application in which all participants were positive regarding the value of the intervention. Participants in two studies with indirect intervention found the application useful and described knowledge of being monitored provided a sense of security[44,45]. Additionally, participants in two studies did not have concerns regarding the continuous geolocation tracking for intervention purpose[43,45], but did stress the importance of transparency regarding the use of this data[43]. Finally, in one interactive study, participants contributed to the creation and curation of geofenced hot zones as well as the prevention messages received when hot zones were triggered, accounting for 67% of hot zones created and used by the study[23].

Place-based mechanisms

Four studies utilized a behavioral mechanism in their geofencing intervention.[23,43,47,48] Four studies utilized a social mechanism which included informational support such as existence of a rural dental clinic[42] and availability of menu grocery store items that were low in sodium.[23,42,47,48] Additionally, participants were able to interact with counselors though the application and review their data concerning visiting high-risk locations for further intervention[47] or sharing context specific messages with other users on the application.[23] Finally, five studies utilized a cognitive mechanism that provided the participant a sense of safety, security, or knowing that their information was captured.[46,47] These included reporting to care teams when the participants

were hospitalized[18,44], capture of time and effort spent working in a clinical environment[45,46], and participants counselor viewing their location and interacting with their place-based data of proximity and time spent in high-risk areas for binge drinking.[47]

Reporting and quality measures

From the 16-point checklist, all included studies reported on 6 items (Suplemental Table 2). Position Health[44], Stat![46], and ResQ[45] studies described how the intervention and data collected integrated into an existing health information system and described some data security procedures. A-CHESS[47] and the Wright et al.,[41] intervention conducted some cost assessment regarding the delivery of the intervention or cost to the participant to utilize the participant. Finally, no study reported on compliance of the intervention or data collection mechanism compliance with national guidelines or federal statutes. We did not assess confidence in the body of evidence or risk of bias.

Discussion

The purpose of this review was to describe the use of geofencing as an intervention and mechanisms that were targeted to achieve various health outcomes. A geofence involves creating virtual predefined set of boundaries or "fences" around a geographic location, including using GPS technology. Geofencing methodology can be used in public health research – both in observational and intervention studies. Thus, geofencing can be a valuable tool in intervention research, enabling researchers to study and implement interventions in specific geographic areas. For example, geofencing allows researchers to precisely target specific areas for intervention. In addition, geofencing allows researchers to send location-based notifications (an intervention) to participants, including on their mobile devices. We identified only 9 studies that fit criteria and

as expected, most publications were relatively recent. We found that the design of the geofencing intervention varied yet acceptability was good among study participants and impact was not assessed in all studies.

Of the studies included, only one was focused on a sexual and gender minority sample and only one with majority Black, Indigenous People of Color (BIPOC), who experience disparities on a vast number of health outcomes due to social and structural factors such as racism and homophobia.[23] Lack of inclusion of these populations is a significant gap that should be monitored as more studies are conducted. In addition, most studies were in the U.S. (North America) with no studies in developing countries, South America, Africa or Asia, which could represent an important opportunity.

The included studies described a range of user input of the geofenced locations from researcher only selection to user selection. This characteristic of an intervention merits consideration. User selection of geofenced locations may be prone to bias and recall issues.[49] Researcher selected locations may not consider the variability of their sample's place-based contexts and may under count locations that should be geofenced. The hybrid approach has the potential to address both limitations. Future studies using geofencing technology may warrant comparative studies of the user input approaches and be specific about the rationale for the type of locations that are geofenced and the user input of these so that studies can be comparable and be conducted in non-western contexts.

Some of the interventions explicitly identified a theoretical model or foundation, and all the studies described targeting at least one of the mechanisms of action from our proposed framework. The studies in which the geofencing intervention targeted the cognitive mechanism were primarily addressing surveillance of the participants and messages to cue cognitions about

their location. Cueing is a significant component of many effective interventions as they serve as reminders to engage in behaviors of interest.[50-52] For example, wearing a bracelet that has a phrase as a reminder to take medication. Cues can focus on both the protective and risk dimensions of the mechanism. For example, if an individual triggers a geofence of a place they have identified as associated with a sense of control, a geofencing intervention could sent a text message that reminds the individual to to engage in self-care. In places where stigma is anticipated a geofencing intervention can send a text message that reminds the individual about adaptive coping behaviors.

Studies utilizing the behavioral mechanism described very specific behavioral targets such as buying lower sodium food, avoiding places of alcohol use, condom use and smoking cessation. As building self-efficacy is a well-established theoretical construct necessary for behavioral change[24], future studies should include opportunities to watch the desired behaviors be role-modeled and practiced to enhance the efficacy of the geofencing intervention.[53]

Studies that utilized the social mechanism were focused on the provision of both informational and emotional support. One study included a component in which the participants could create messages for other user of the geofencing application. As there are different types of social support (e.g., emotional, appraisal, economic and informational) future studies should be specific and transparent about the types being targeted. With additional geofencing studies, a future review can be conducted using meta-analytic methods to determine the quantitative effectiveness of geofencing interventions in population health research.

Limitations

The search strategy was limited to English articles in PubMed, CINAHL, EMBASE Web of Science, Cochrane, and PsychINFO and we acknowledge other publications may not have been captured with these. There was heterogeneity in how studies reported intervention development, theoretical frameworks, and feasibility and acceptability of the intervention. This reduced the ability to properly assess the extent of behavioral mechanism utilized for the given outcome. Additionally, as geofencing is a new technology, not many peer-reviewed articles have been published and this scoping review chose to exclude conference abstracts.

Conclusions

In conclusion, this scoping review indicates that geofencing is an emerging acceptable and feasible intervention that has been applied to a variety populations and health outcomes.[23] Attention to the mechanisms of actions will enable the field to understand not only whether geofencing is an appropriate and effective intervention but why it works to achieve the outcomes we observe. There is a need for future research that includes sexual and gender minority and BIPOC populations and populations from non-Western contexts to achieve the Health People Framework objectives given the persistent findings that BIPOC and SGM populations. These studies could address those health outcomes where disparities are stark such as HIV/AIDS, cardiovascular, diabetes, COVID-related and mpox. Finally, future research can reveal place-based contexts that have not been considered which can inform resource allocation and targets for health-promoting policies.

Figure Caption: Types of mechanisms of action, protective and risk factors as well as spatial scales in geofencing interventions in population health research.

Contributorship statement

Drs. Tobin and Heidari contributed equally to this manuscript.
KT, OH and DD planned the study.
KT, OH, CV and SS acquired data and conducted the analysis for this study.
KT, OH and DD equally contributed to writing and finalizing the manuscript.

Competing interests

Karin E. Tobin, Omeid Heidari, Connor Volpi, Shereen Sodder and Dustin T. Duncan declare that they have no conflict of interest.

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Data sharing statement

All data relevant to the study are included in the article or uploaded as supplementary information

Ethics Approval

Ethics approval was not required as the scoping review is based on published studies,

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Figure 1. Types of mechanisms of action, protective and risk factors as well as spatial scales in geofencing interventions in population health research.

Mechanisms of Action	**Protective**	**Risk**	Spatial Scales
Cognitive	Sense of control Self-efficacy	Internalized & anticipated stigma Risk perceptions	Room Home Block Neighborhood City County State Region Nation Globe
Behavioral	Adaptive Coping Self-care	Substance use Non-adherence to medication	
Social	Instrumental & Emotional support	Enacted stigma Conflict	

Table 1. **Details of nine studies that met inclusion criteria for the scoping review**

Name/citation Geofenced intervention Refernce number	Study characteristics	Development of geofence	Results	Theory and framework
Wright et al., 2021 Vendor not cited 41	*Study purpose:* Increase awareness and use of dental services in a rural clinic *Study design:* Pre and post intervention community and outcome assessments *Target population:* Residents of a rural zip code surrounding a dental clinic *Sample size:* 516,073 impressions delivered to individuals crossing the geofence *Duration of follow-up:* Impressions were sent over a 60-day period *Outcome of interest:* Number of impressions displayed to a user, clicks on the banner, click-through rates on the dental website from the banner, and pre/post intervention community knowledge of the dental clinic	*User input:* None *Mechanism of delivery:* Any individual with a smartphone physically located within the boundaries of three zip codes near the dental clinic received a geofence message advertising the dental clinic with webpage information for additional information	Over 60 days, 516,073 impressions were delivered, with 475 individuals clicks on the banner to get website information, and a click through rate of 0.09%. Increases were seen in community knowledge about the clinic (p=0.045) and dental visits by respondent or a family member (p=0.04) post intervention	*Theoretical framework:* Anderson Model of Health Services Use *Behavioral* *Social:* Informational support of an existing service that is place-based *Cognitive*

Owei et al., 2021 ResQ 44	*Study purpose:* Assess the impact of the ResQ geofencing app on submission rates for duty hours and number of violations reported *Study design:* Mixed methods feasibility and acceptability of the ResQ app. *Target population:* Residents from the General Surgery Residency Program *Sample size:* 23 *Duration of follow-up:* 60 days *Outcome of interest:* Comparison of reported and recorded work hours submitted and work hour violations (80 hours per week and continuous hours worked). Additionally, 13 participants participated in semi-structured interviews to understand acceptability and feasibility of ResQ.	*User input:* None *Mechanism of delivery:* Geofences were placed around clinical sites where residents worked. The ResQ application was installed on resident's work phones and recorded work hours based on entering and exiting the geofence.	The mean number of violations decreased significantly (p=0.04) and work hour submissions did not differ with the intervention (p=0.42). Compared to the previous year, reported violations significantly decreased (p<0.01). Participants found the application useful for recording and reporting clinical hours and eased administrative burden.	*Theoretical framework:* None listed *Behavioral* *Social* *Cognitive:* Sense of safety in capture and reporting of clinical hours
Gustafson et al., 2014 A-CHESS 46	*Study purpose:* Determine if a smartphone application to support recovery from alcohol use disorders reduced risky drinking days. *Study design:* Unmasked randomized clinical trial	*User input:* High-risk locations were identified by participants *Mechanism of delivery:* Study team geofenced user	Along with the geofenced intervention, A-CHESS was a mobile application that provided monitoring, information, communication, and support services from counselors. Overall the A-	*Theoretical framework:* Self-determination theory *Behavioral:* Warning messages sent in risky areas

	Target population: People with diagnosed alcohol dependence discharged from residential treatment *Sample size:* 349 *Duration of follow-up:* 8 months *Outcome of interest:* Risky drinking days in the previous 30 days	identified high-risk locations and sent alerts to the user's smartphone asking if they wanted to be there	CHESS group reported fewer risky drinking days at follow-up (p=0.003)	*Social:* Informational support with counselors *Cognitive:* Passive and real-time capture of information shared with counselors
Nguyen et al., 2017 Ginger.io 18	*Study purpose:* Evaluate the use of smartphone-based geofencing for tracking hospitalizations *Study design:* Remote and in-person arm validation of1 a mobile application that detected hospitalizations and length of hospitalization *Target population:* Remote- participants from the Health eHeart study with a smartphone In-person- Patients scheduled for electrophysiology and cardiac catheterization procedures. *Sample size:* Remote- 3,443; In person- 22	*User input:* None *Mechanism of delivery:* The app was programmed with all U.S. hospitals geofenced. A notification was sent to within 1 hour of leaving the hospital vicinity asking participants to confirm if they received medical care	Remote- The application detected 800 unique participants in a geofenced location with a positive predictive value between 65-78% based on how hospitalization was confirmed. Most common error in detection was the participant was a medical center employee. In person- Visits were detected in 17/22 with confirmed hospitalization. Mean visit duration was not correlated with actual hospital length of stay.	*Theoretical framework:* None listed *Behavioral* *Social* *Cognitive:* Sense of safety in provider knowing your hospitalization status

	Duration of follow-up: Remote- mean of 260 days; In person- Duration of their scheduled procedure *Outcome of interest:* Detection of hospitalization			
Naughton et al., 2016 Q Sense 20	*Study purpose:* Feasibility and acceptability of a mobile application using geofencing to deliver tailored place-based intervention messages *Study design:* Explanatory sequential mixed methods *Target population:* Tobacco smokers willing to set a quit date within 1 month *Sample size:* 15 in quantitative arm and 13 qualitative interviews *Duration of follow-up:* Pre-quit period (up to 1 month) and 2 weeks post-quit date *Outcome of interest:* 1) User engagement with app; 2) Assess app's location-sensing accuracy; 3) Feasibility of geofence mechanism; 4) Limitations of everyday use of app	*User input*: Geofences based on user habits and reports of smoking locations *Mechanism of delivery:* If a smoker reported smoking in the same proximity, the device created a geofence around that area with a radius of 100m. When a user entered the geofence for greater than 5 minutes a location-tailored support messaged was triggered	User engagement with the application varied from 60% of days pre-quit and 39% post-quit (52% excluding outliers). Geolocation was collected on 97% of smoking reports with high accuracy. A mean of 1.5 geofences were created per participant with 87% having at least one. 5/9 participants eligible to receive a geofenced triggered message received at least one. Environmental constraints and forgetfulness were common reasons for forgetting to engage with app. Participants were positive about the value of the geofenced support	*Theoretical framework:* Learning theory and taxonomy of smoking behavior change *Behavioral:* Coping and resilience regarding smoking triggers *Social* *Cognitive*

			and had no privacy concerns.	
Dorsch et al., 2020 LowSalt4Life 47	*Study purpose:* Effectiveness of the LowSalt4Life mobile app on maintaining a low sodium diet and controlling blood pressure *Study design:* Unblinded randomized control trial *Target population:* Adults diagnosed with hypertension and taking antihypertensive medication *Sample size:* 50 randomized *Duration of follow-up:* 8 weeks *Outcome of interest:* Changes in 24-hour dietary recall and sodium intake, urine sodium excretion, blood pressure	*User input:* Mixed. Geofences were created based on user input as well as from a predictive service when a participant entered a grocery store, restaurant, or home. *Mechanism of delivery:* Contextual adaptive messages were sent to participant's phones when entering a geofence, with messages linked to content in the mobile application	There was a significant decrease in sodium excretion (p=0.03) and decrease in sodium intake via 24 hour dietary recall (p=0.01) and in the App group vs no App groups. Blood pressure decreased by 1.7 mmHg in the App group compared to 0.7 in the no App, but the change was not significant (p=0.12).	*Theoretical framework:* Theory of Planned Behavior *Behavioral:* Dietary messages sent when participant is in areas where they would purchase/consume food *Social:* Informational support regarding which products and food choices had lower sodium in context of place *Cognitive*
DeFilippis et al., 2017 Position Health 43	*Study purpose:* Determine the feasibility of patients with ventricular assist devices care engagement with and feasibility of a geofencing notification system. *Study design:* Feasibility study with quantitative and qualitative measures	*User input:* None *Mechanism of delivery:* Geofences were drawn around emergency departments (ED)	The system was actIve on 4 occasions, each of which the participant confirmed they were at or near the hospital but were not seeking care. 1 patient	*Theoretical framework:* None listed *Behavioral* *Social*

	Target population: Adults with a ventricular assist device (VAD) *Sample size:* 21 *Duration of follow-up:* 6 months *Outcome of interest:* Proper detection of emergency department utilization by participant and satisfaction with mobile application.	across the U.S. Once the application detected that a participant approached an ED, a prompt was sent to their phone to confirm if they were seeking care at that hospital. If yes, another prompt asked the participant to confirm if the app could notify their VAD healthcare team. If 'yes' to both, a notification was sent to the covering provider's pager with participant name and contact.	reported seeking ED care but did not receive a ping. Most patients responded favorable to their impression of the application stating that it "gave them peace of mind."	*Cognitive*: Sense of safety to participants that emergency room and hospitalizations could alert their VAD provider regarding the need to coordinate care
Connor & Herzig, 2016 Stat! 45	*Study purpose:* Determine the feasibility and acceptability of a mobile application that allow automatic capture of work hours without manual employee input *Study design:* Feasibility study	*User input:* None *Mechanism of delivery:* Geofences were drawn around hospitals where the anesthesia group provided services.	Use of the geofencing application showed a significant correlation of early departures following late departures the previous day ($p<0.01$ in 73 of 91 occasions), and better dispersion of	*Theoretical framework:* None listed *Behavioral* *Social*

	Target population: Anesthesia providers in a private practice group *Sample size:* 198 *Duration of follow-up:* 12 months *Outcome of interest:* Equitable workload distribution, employee acceptance and uptake, and reduced dispersion of the amount of overtime worked by staff	When the provider enters a geofence, their time at the facility is continuously checked and reported to a central server. Reports were then used to inform future clinical responsibilities and overtime worked	working hours (p=0.002) compared to the previous year. Acceptance of the mobile application was slow to start but >95% in less than 1 year of roll out	*Cognitive:* Sense of security regarding equitable distribution of work based on geofenced data and capture of time working for billing purposes
Besoain et al., 2020 UBESafe 22	*Study purpose:* Prevent sexually transmitted infections (STIs) by sending preventive measures in risky situations *Study design:* Development and feasibility *Target population:* Men who have sex with men *Sample size:* Development-5; Feasibility- 4 *Duration of follow-up:* Development- 2 weeks; Feasibility- 1 month *Outcome of interest:* Development- functional testing to receive user feedback; Feasibility- try the UBESAFE system with all its functionalities	*User input:* Mixed. Hot zones were created by a system administrator and with input from users *Mechanism of delivery:* Geofenced hot zones are areas demines with a high probability for intercourse. When users enter a hot zone, a contextual message to prevent HIV and STIs, and promote testing	All users triggered a geofenced hotzone during the development phase, though this was not quantified further. Hot zones were seen as a necessary component from those testing in the development phase. In the feasibility phase, users tested and rated prevention messages as well as adding their own. Users also contributed to hot zones and tested existing ones, contributing	*Theoretical framework:* Elaboration likelihood model *Behavioral:* Contextual messages for sexual risk reduction sent in hot spots for high-risk intercourse *Social:* Gamification of preventive messages and interaction with

			65% of hot zones in the application at the end of the study.	others using the application *Cognitive*

Supplemental Table 2. **Components of mobile health evidence reporting and assessment.**

	Wright et al., 2021	Owei et al., 2021	Gustafson et al., 2014	Nguyen et al., 2017	Naughton et al., 2016	Dorsch et al., 2020	DeFilippis et al., 2017	Connor & Herzig, 2016	Besoain et al., 2020
Infrastructure	■	■	■	■	■	■	■	■	■
Technology platform	■	■	■	■	■	■	■	■	■
Interpretability/Health information systems context		■					■	■	
Intervention delivery	■	■	■	■	■	■	■	■	■
Intervention content	■	■	■	■	■	■	■	■	■
Usability/content testing					■		■	■	■
User feedback		■		■	■		■	■	■
Access of individual participants		■	■	■	■		■	■	■
Cost assessment	■		■						
Adoption inputs/program entry	■	■	■	■	■	■	■	■	■
Limitations for delivery at scale		■		■	■				
Contextual adaptability					■				
Replicability			■			■	■	■	■
Data security							■	■	
Compliance with national guidelines or regulatory statutes									

Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Checklist

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
TITLE			
Title	1	Identify the report as a scoping review.	
ABSTRACT			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	
METHODS			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.	
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	
Information sources*	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	
Selection of sources of evidence†	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	
Data charting process‡	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	
Critical appraisal of individual sources of evidence§	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
RESULTS			
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	
DISCUSSION			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	
Limitations	20	Discuss the limitations of the scoping review process.	
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	
FUNDING			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	

JBI = Joanna Briggs Institute; PRISMA-ScR = Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews.

* Where *sources of evidence* (see second footnote) are compiled from, such as bibliographic databases, social media platforms, and Web sites.

† A more inclusive/heterogeneous term used to account for the different types of evidence or data sources (e.g., quantitative and/or qualitative research, expert opinion, and policy documents) that may be eligible in a scoping review as opposed to only studies. This is not to be confused with *information sources* (see first footnote).

‡ The frameworks by Arksey and O'Malley (6) and Levac and colleagues (7) and the JBI guidance (4, 5) refer to the process of data extraction in a scoping review as data charting.

§ The process of systematically examining research evidence to assess its validity, results, and relevance before using it to inform a decision. This term is used for items 12 and 19 instead of "risk of bias" (which is more applicable to systematic reviews of interventions) to include and acknowledge the various sources of evidence that may be used in a scoping review (e.g., quantitative and/or qualitative research, expert opinion, and policy document).

From: Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA Extension for Scoping Reviews (PRISMAScR): Checklist and Explanation. Ann Intern Med. 2018;169:467–473. doi: 10.7326/M18-0850.

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Use of geofencing interventions in population health research: a scoping review

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Abstract

Objectives: Technological advancements that utilize global positioning system (GPS), such as geofencing, provide the opportunity to examine place-based context in population health research. This review aimed to systematically identify, assess, and synthesize the existing evidence on geofencing intervention design, acceptability, feasibility, and/or impact.

Design: Scoping review, using the PRISMA-ScR guidance for reporting.

Data sources: PubMed, CINAHL, EMBASE Web of Science, Cochrane, and PsychINFO for articles in English published up to December 31st, 2021.

Eligibility criteria: Articles were included if geofencing was utilized as a mechanism for intervention delivery. Exclusion criteria: 1) a component or combination of GPS, geographic information system (GIS), or ecological momentary assessment (EMA) was utilized without delivery of an intervention; 2) did not include a health or health-related outcome from the geofencing intervention; or 3) was not a peer-reviewed study.

Data extraction and synthesis: Several researchers independently reviewed all abstracts and full-text articles for final inclusion.

Results: A total of 2,171 articles were found; after exclusions, nine studies were included in the review. The majority were published in five years preceding the search (89%). Geofences in most studies (n=5) were fixed and programmed in the mobile application carried by participants without their input. Mechanisms of geofencing interventions were classified as direct or indirect, with five studies (56%) utilizing direct interventions. There were several different health outcomes (from smoking to problematic alcohol use) across the five studies that utilized a direct geofencing intervention.

Conclusions: This scoping review found geofencing to be an emerging technology that is an acceptable and feasible intervention applied to several different populations and health outcomes. Future studies should specify the rationale for the locations that are geofenced and user input. Moreover, attention to mechanisms of actions will enable scientists to understand not only whether geofencing is an appropriate and effective intervention but why it works to achieve the outcomes observed.

Strengths and limitations of this study

- The scoping review was comprehensive, utilizing rigorous searches of six databases.
- The review used the Preferred Reporting Items for Systematic Reviews and Meta-analyses extension for Scoping Reviews (PRISMA-ScR) checklist to guide reporting.
- Most of the eligible studies were conducted in the United States, limiting generalizability to other international settings.
- The review was conducted through the published literature through 2021 and therefore does not include more recent publications.

Introduction

Population health outcomes and health disparities result from multi-level factors beyond the individual. For example, poverty can lead to a lack of access to healthy food[1] and medical care[2]; unstable housing can lead to inability to adhere to medications[3] and exposures to unhealthy environments;[4] homophobia and racism leads to stigma and discrimination, and mistrust and avoidance of medical systems.[5-7]

Often in behavioral research, theories or frameworks do not consider the place-based context of behavior despite literature on the consistent and enduring impact of places such as neighborhoods and communities on population health outcomes and disparities.[8-10] Place-based context can be conceptualized as both geographic areas defined by boundaries or as socially constructed out of symbolic meanings *and* social relations.[11,12] In both cases, place-based context operates to perpetuate hierarchical social structures, facilitate and constrain resources, and protect or hinder health. Moreover, place-based context may facilitate specific health-related interactions such as drug or alcohol use, experiences of violence, or engagement in healthcare. Yet behavioral interventions often conceptualize place-based context as static (e.g., place of risky sex) and do not consider how place-based contexts vary over time. Real-time geospatial methods, including the use of global positioning system (GPS) technology, are the cutting-edge, best-suited methods to overcome limitations of most neighborhoods and other environments health research because they better capture place-based contexts corresponding to individuals' lived experiences, referred to as "activity space".[13]

There are numerous types of GPS-based methods that collect data from individuals and in some cases deliver intervention content. For example, ecological momentary assessment (EMA) has been shown to be an acceptable method of data collection.[14] Ecological Momentary

Interventions (EMI) allow researchers to deliver intervention content through mobile devices.[15] Just-in-time adaptive interventions (JITAI) attempt to address the changing needs of an individual where the intervention algorithm is programmed to determine if and what intervention content should be delivered to participants at set times throughout the day, whenever a participant requests one, or based on the participant's current state (e.g., stress) or environmental changes (e.g., weather).[16-17] Finally, geofences are virtual boundaries drawn around a location and allow for monitoring and messaging when individuals enter or exits the geofenced parameter.[18] Geofencing interventions are a subset of JITAI where there is continuous monitoring of the participant's location using GPS and delivery of an intervention such as text messages or links to health information or information about health services that are in the area based on a spatial context trigger. A geofence involves creating virtual predefined set of boundaries or "fences" around a geographic location, including using GPS technology. Geofencing methodology can be used in public health research – both in observational and intervention studies. Thus, geofencing can be a valuable tool in intervention research, enabling researchers to study and implement interventions in specific geographic areas. For example, geofencing allows researchers to precisely target specific areas for intervention. In addition, geofencing allows researchers to send location-based notifications (an intervention) to participants, including on their mobile devices. One example of this in the public health setting is the use of geofencing to monitor movements of individuals who tested positive for COVID-19 virus.[19]

Reviews of JITAI and EMI show the promising potential of this evolving technology,[20-22] yet, such reviews are noted to lack the inclusion of geofencing, representing a major gap in the literature. This gap is vital to address as geofencing has the capability to address an array of

different health issues ranging from tobacco cessation to HIV medication adherence. The lack of a clear and systematic understanding of the scope of geofencing interventions undermines its potential to impact population health. The purpose of this scoping review is to describe of the state of the evidence on geofencing intervention design, acceptability, feasibility, and impact. In addition, we examine what behavioral mechanisms were targeted across the interventions assessed.

Conceptualizing mechanisms of action

Another limitation in the literature of EMA and JITAI interventions is the lack of attention to specific mechanisms of action that operate to achieve outcomes.[23] Therefore, we sought to develop a framework based on several complementary theories and frameworks (e.g., Turan's HIV Stigma Framework and Social Cognitive Theory[24-26]) to evaluate geofencing interventions included in this review. The framework posits three key mechanisms operate for place-based context to influence health outcomes (Figure 1). Each mechanism has both a protective and risk dimension. The Cognitive mechanism includes cognitive processes such as sense of control, knowledge, attitudes, self-efficacy, maladaptive thoughts, risk perceptions and internalized stigma.[27-32] The Behavioral mechanism refers to both protective behaviors such as adaptive coping as well as risky behaviors such substance use, condomless sex and non-adherence to medication and care.[33-35] The Social mechanism refers to interactions with others in the personal social networks and broader community such as emotional or instrumental support or enacted stigma and conflict which have been shown to exacerbate or mitigate health outcomes.[36-38] The framework can be applied to multiple spatial scales from a micro-level (e.g. a room in one's

residence) to community-level (e.g. a neighborhood activity space or census tract) to macro (e.g. state, region).

Methods

Study design

This scoping review is reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) extension for Scoping Reviews checklist.[39]

Inclusion criteria

Articles were only included if they utilized geofencing as a mechanism for intervention delivery. Articles were excluded if 1) a component or combination of GPS, geographic information system (GIS), or ecological momentary assessment (EMA) was utilized without delivery of an intervention; 2) did not include a health or health-related outcome from the geofencing intervention; or 3) was not a peer-reviewed study.

Search strategy

Authors first met to develop the list of potential search terms and refined after initial searchers were conducted. Then searches were conducted in PubMed, CINAHL, EMBASE Web of Science, Cochrane, and PsychINFO for articles published through the end of 2021 (Appendix 1, detailed search strategy across n=6 databases). Search terms were for broad concepts regarding mobile delivery of a geofencing intervention: “Geographic Information Systems”; “Georeferencing”; “Global Positioning System”; or “Geofenc*” combined with “Smartphone” or

"Mobile Applications." The search was conducted on 12/1/2021 and was not registered. A protocol was not prepared.

Study selection

Screening of article titles and abstracts was conducted with two reviewers (SS, CV) to maximize scrutiny of all records. Each reviewer independently screened all articles identified from the initial search for relevance to the pre-defined inclusion criteria that was highlighted during a training session where it was emphasized that the reviewers should apply a liberal approach. Next, the same two reviewers independently reviewed each of the full texts for inclusion in the data extraction phase. Any disagreements in both phases were adjudicated by a third reviewer (OH). In all phases reviewers were not blinded to authors, funding, or information regarding publication of all the records.

Data extraction

Two reviewers (OH, KT) extracted data for details of study design, target population, sample size, duration of follow-up, theoretical framework, software or mobile application use, goal, and mechanism of geofenced intervention, and impact of the intervention of outcomes. Place-based mechanisms associated with the intervention included: 1) Behavioral, 2) Social support: Emotional, Instrumental, Informational, and Social monitoring, and 3) Cognitive. Finally, established guidance for reporting health intervention using mobile phone was utilized to evaluate the quality of each article.[40]

Patient and Public Involvement

None.

Results

Included studies

Using the search strategy in six identified databases, a total of 2,171 articles were found after removing duplicates. 2,039 (94%) studies were irrelevant and 132 (6%) full text studies were assessed for eligibility. Reasons for exclusion of the 123 articles in the full-text phase included the article not being peer reviewed (n=46, 37%), review articles (n=19, 16%), was not the correct study design or intervention (n=14, 11%), or utilized a combination of GPS, GIS, and or Ecological Momentary Assessment, but was not a geofencing intervention (n=44, 36%). Nine eligible studies were ultimately included in this scoping review (Figure 2; Appendix 2, Details of nine studies that met inclusion for the scoping review).

Study characteristics

The majority were published in five years preceding the search (n=8; 89%). Most employed a pre/post study design to assess changes in measured outcome or feasibility and acceptability of the geofencing intervention (n=7; 78%) with two unblinded randomized control trials. Sample sizes ranged from 4 to 3,443; one study's intervention quantified its reach with the geofencing intervention displaying on 516,073 mobile phones, though these impressions do not represent unique individuals receiving the intervention.[41] Most studies (n=7; 78%) were conducted in the United States, one in the United Kingdom[42] and one in Spain.[23] A description of studies, including the names of the mobile applications used, study design and characteristics, and place-based mechanisms are detailed in Appendix 2. The design of the geofencing interventions varied

based on user input and content delivery (Appendix 3, Components of mobile health evidence reporting and assessment).

Geofencing methods: user input

Geofences in most studies (n=5) were fixed and programmed in the mobile application without participant input. These included hospital emergency departments,[18,43] hospitals where participants worked.[44,45] and a specific rural dental clinic.[41] Two studies utilized participants input in determining where to geofence related to smoking[42] or problematic alcohol use.[46] Two studies utilized a mix of fixed and user input. Dorsch et al. utilized user input to geofence locations where foods were consumed or purchased as well as a cloud-based web service to predict when participants entered grocery stores or restaurants. Besoain et al., used a moderated system where participants suggested locations to geofence that were venues for high-risk sexual encounters, but these venues were moderated by the study team and locations could be added or removed.

Intervention content delivery: direct versus indirect

Intervention content was delivered in direct or indirect methods. Five studies (56%) sent participants intervention content directly to their phones based on triggering the geofence boundary. These interventions included informing individuals living in a rural area of a dental clinic[41] or sending behavioral messages regarding problematic alcohol use when near a bar,[46] smoking cessation in areas detected as high likelihood of smoking,[42] making low-sodium diet choices in grocery stores, restaurants, or at home, or HIV and STI prevention messages when in venues associated with high-risk sexual activity.[23] The remaining 4 studies were categorized as

indirect as they collected data when participants triggered geofence boundaries and in some cases delivered content at a later time from when the fence was triggered.

Impact of the interventions

There was not a consistent health outcome across the five studies that utilized a direct intervention. Both studies that utilized a randomized control design showed improved outcomes in the group randomized to geofencing. A-CHESS sent context and place-based messages and included multiple other services such as a phone and data plan, access to a virtual counselor, and other interactive features.[46] LowSalt4Life contained features including low sodium options and alternatives at grocery stores or restaurants, and the ability to scan product barcodes to find similar low sodium options. Q Sense intervention participants decreased from 60% of pre-quit smoking days to 39% post-quit. UBESafe intervention reported that all participants were able to trigger a hot zone where sexual contacts often took place and received a place-based prevention message.[22] Finally, Wright et al.,[41] used a pre/post design, and found increases in community knowledge about the dental clinic ($p=0.045$) and increased number of dental visits post intervention.

Indirect intervention outcomes

Two studies used the geofence to track time working from medical practitioners or surgical residents. Owei et al., found the mean number of working hour violations for surgical residents' post-intervention significantly decreased ($p=0.04$) compared to pre-intervention and compared to the previous year ($p<0.01$).[44] Connor et al., showed a significant correlation of early departures from operating room duties following late departures the previous day ($p<0.01$) and better

dispersion of working hours (p=0.002) compared to the previous year.[45] Two other studies geofenced major hospitals to detect hospitalization of high priority patients. Nguyen et al., found the geofenced mobile application detected 800 unique participants who triggered a geofence, with a predictive value of true hospitalization between 65-78%.[18] Similarly, from a sample size of 21, 4 of the participants activated the alert system for patients with a ventricular assist device to their on-call care team when they triggered an emergency room geofence.[43]

Acceptability measures

Five studies reported data regarding acceptability of the geofencing mobile application in which all participants were positive regarding the value of the intervention. Participants in two studies with indirect intervention found the application useful and described knowledge of being monitored provided a sense of security.[43,44] Additionally, participants in two studies did not have concerns regarding the continuous geolocation tracking for intervention purpose,[42,44] but did stress the importance of transparency regarding the use of this data.[42] Finally, in one interactive study, participants contributed to the creation and curation of geofenced hot zones as well as the prevention messages received when hot zones were triggered, accounting for 67% of hot zones created and used by the study.[23]

Place-based mechanisms

Four studies utilized a behavioral mechanism in their geofencing intervention.[23,42,46,47] Four studies utilized a social mechanism which included informational support such as existence of a rural dental clinic[41] and availability of menu grocery store items that were low in sodium.[23,41,46,47] Additionally, participants were able to interact with counselors though the application and

review their data concerning visiting high-risk locations for further intervention[46] or sharing context specific messages with other users on the application.[23] Finally, five studies utilized a cognitive mechanism that provided the participant a sense of safety, security, or knowing that their information was captured.[45,46] These included reporting to care teams when the participants were hospitalized,[18,43] capture of time and effort spent working in a clinical environment,[44,45] and participants counselor viewing their location and interacting with their place-based data of proximity and time spent in high-risk areas for binge drinking.[46]

Reporting and quality measures

All included studies reported on at least six items (Appendix 3). Position Health,[43] Stat!,[45] and ResQ[44] reported on how the intervention and data collected integrated into an existing health information system and described some data security procedures. CHESS[46] and the Wright et al.[41] intervention conducted some cost assessment regarding the delivery of the intervention or cost to the participant to utilize the participant. No study reported on compliance of the intervention or data collection mechanism compliance with national guidelines or federal statutes. We did not assess confidence in the body of evidence or risk of bias.

Discussion

The purpose of this scoping review was to describe the use of geofencing as an intervention and mechanisms that were targeted to achieve various health outcomes. A geofence involves creating virtual predefined set of boundaries or "fences" around a geographic location, including using GPS technology. Geofencing methodology can be used in public health research – both in observational and intervention studies. Thus, geofencing can be a valuable tool in intervention

research, enabling researchers to study and implement interventions in specific geographic areas. For example, geofencing allows researchers to precisely target specific areas for intervention. In addition, geofencing allows researchers to send location-based notifications (an intervention) to participants, including on their mobile devices. We identified only nine studies that fitted the criteria and, as expected, most publications were relatively recent. We found that the design of the geofencing intervention varied yet acceptability was good among study participants and impact was not assessed in all studies.

Of the studies included, only one was focused on a sexual and gender minority sample and only one with majority Black, Indigenous People of Color (BIPOC), who experience disparities on a vast number of health outcomes due to social and structural factors such as racism and homophobia.[23] Lack of inclusion of these populations is a significant gap that should be monitored as more studies are conducted. In addition, most studies were conducted in the United States, with no studies in developing countries, South America, Africa or Asia, which could represent an important opportunity.

The included studies described a range of user input of the geofenced locations from researcher only selection to user selection. This characteristic of an intervention merits consideration. User selection of geofenced locations may be prone to bias and recall issues.[48] Researcher selected locations may not consider the variability of their sample's place-based contexts and may under count locations that should be geofenced. The hybrid approach has the potential to address both limitations. Future studies using geofencing technology may warrant comparative studies of the user input approaches and be specific about the rationale for the type of locations that are geofenced and the user input of these so that studies can be comparable and be conducted in non-western contexts.

Some of the interventions explicitly identified a theoretical model or foundation, and all the studies described targeting at least one of the mechanisms of action from our proposed framework. The studies in which the geofencing intervention targeted the cognitive mechanism were primarily addressing surveillance of the participants and messages to cue cognitions about their location. Cueing is a significant component of many effective interventions as they serve as reminders to engage in behaviors of interest.[49-51] For example, wearing a bracelet that has a phrase as a reminder to take medication. Cues can focus on both the protective and risk dimensions of the mechanism. For example, if an individual triggers a geofence of a place they have identified as associated with a sense of control, a geofencing intervention could sent a text message that reminds the individual to engage in self-care. In places where stigma is anticipated a geofencing intervention can send a text message that reminds the individual about adaptive coping behaviors.

Studies utilizing the behavioral mechanism described very specific behavioral targets such as buying lower sodium food, avoiding places of alcohol use, condom use and smoking cessation. As building self-efficacy is a well-established theoretical construct necessary for behavioral change,[24] future studies should include opportunities to watch the desired behaviors be role-modeled and practiced to enhance the efficacy of the geofencing intervention.[52]

Studies that utilized the social mechanism were focused on the provision of both informational and emotional support. One study included a component in which the participants could create messages for other user of the geofencing application. As there are different types of social support (e.g., emotional, appraisal, economic and informational) future studies should be specific and transparent about the types being targeted. With additional geofencing studies, a

future review can be conducted using meta-analytic methods to determine the quantitative effectiveness of geofencing interventions in population health research.

Limitations

The search strategy was limited to English articles in PubMed, CINAHL, EMBASE Web of Science, Cochrane, and PsychINFO and we acknowledge other publications may not have been captured with these. There was heterogeneity in how studies reported intervention development, theoretical frameworks, and feasibility and acceptability of the intervention. This reduced the ability to properly assess the extent of behavioral mechanism utilized for the given outcome. Additionally, as geofencing is a new technology, not many peer-reviewed articles have been published and this scoping review chose to exclude conference abstracts.

Conclusions

This scoping review found geofencing to be an emerging technology that is an acceptable and feasible intervention applied to several different populations and health outcomes.[23] Attention to the mechanisms of actions will enable the field to understand not only whether geofencing is an appropriate and effective intervention but why it works to achieve the outcomes we observe. There is a need for future research that includes sexual and gender minority and BIPOC populations and populations from non-Western contexts to achieve the Health People Framework objectives given the persistent findings that BIPOC and SGM populations. These studies could address those health outcomes where disparities are stark such as HIV/AIDS, cardiovascular, diabetes, COVID-related and mpox. Finally, future research can reveal place-

based contexts that have not been considered which can inform resource allocation and targets for health-promoting policies.

Contributors
Drs. Tobin and Heidari contributed equally to this manuscript. KT, OH and DD planned the study. KT, OH, CV and SS acquired data and conducted the analysis for this study. KT, OH and DD equally contributed to writing and finalizing the manuscript.

Competing interests
We declare that we have no competing interests.

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Data availability statement
No additional data available.

Ethics approval
Ethics approval was not required as the scoping review is based on published studies.

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Figure 1. Types and mechansims of action, protective and risk factors as well as spatial scales in geofencing intrerventions in population health research.

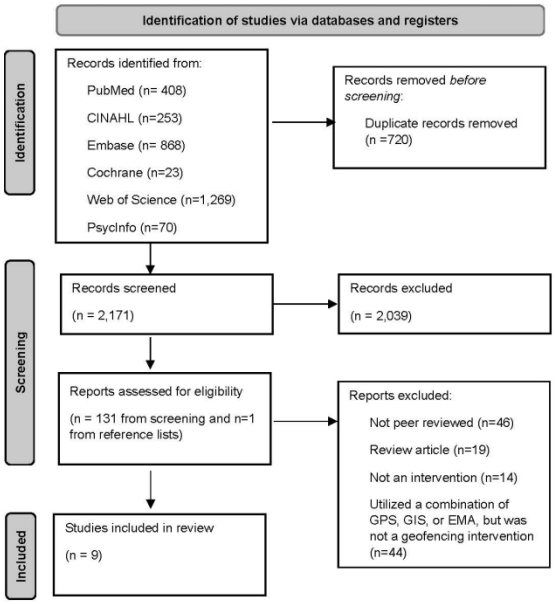
Figure 2. PRISMA flow diagram

Figure 1. Types of mechanisms of action, protective and risk factors as well as spatial scales in geofencing interventions in population health research.

Mechanisms of Action	Protective	Risk	Spatial Scales
Cognitive	Sense of control Self-efficacy	Internalized & anticipated stigma Risk perceptions	Room Home Block Neighborhood City County State Region Nation Globe
Behavioral	Adaptive Coping Self-care	Substance use Non-adherence to medication	
Social	Instrumental & Emotional support	Enacted stigma Conflict	

215x279mm (200 x 200 DPI)

Figure 2. PRISMA diagram of selected studies



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Appendix 1. Detailed search strategy across n=6 databases

PubMed

Concept	Search Terms
Mobile applications	("Smartphone"[Mesh]) OR "Mobile Applications"[Mesh] OR smartphon* [tiab] OR "mobile application*" [tw] OR "mobile app" [tw] OR "mobile apps" [tw] OR "mobile phon*" [tw]
Geofencing	"Geographic Information Systems"[Mesh] OR "Geographic Information System" [tw] OR "Geographical Information System" [tw] OR "Geographical Information Systems" [tw] OR "Georeferencing" [tw] OR "Global Positioning System" [tw] OR "Global Positioning Systems" [tw] OR "Geofenc*" [tw]

Embase

Concept	Search Terms
Mobile applications	'mobile phone'/exp OR 'wireless communication'/exp OR 'mobile application'/exp OR smartphon*:ti,ab,kw OR 'mobile application*':ti,ab,kw OR 'mobile app':ti,ab,kw OR 'mobile apps':ti,ab,kw OR 'mobile phon*':ti,ab,kw
Geofencing	'geographic information system'/exp OR 'global positioning system'/exp OR 'geographic information system':ti,ab,kw OR 'geographical information system':ti,ab,kw OR 'geographical information systems':ti,ab,kw OR 'georeferencing':ti,ab,kw OR 'global positioning system':ti,ab,kw OR 'global positioning systems':ti,ab,kw OR 'geofenc*':ti,ab,kw

CINAHL

Concept	Search Terms
Mobile applications	(MH "Smartphone") OR (MH "Cellular Phone+") OR (MH "Text Messaging+") OR (MH "Mobile Applications") OR smartphon* OR "mobile application*" OR "mobile app" OR "mobile apps" OR "mobile phon*"
Geofencing	(MH "Geographic Information Systems+") OR "Geographic Information System" OR "Geographical Information System" OR "Geographical Information Systems" OR "Georeferencing" OR "Global Positioning System" OR "Global Positioning Systems" OR Geofenc*

Cochrane

Concept	Search Terms
Mobile applications	([mh Smartphone]) OR [mh "Mobile Applications"] OR smartphon*:ti,ab OR ("mobile" NEXT application*):ti,ab,kw OR "mobile app":ti,ab,kw OR "mobile apps":ti,ab,kw OR ("mobile" NEXT phon*):ti,ab,kw

Geofencing	[mh "Geographic Information Systems"] OR "Geographic Information System":ti,ab,kw OR "Geographical Information System":ti,ab,kw OR "Geographical Information Systems":ti,ab,kw OR Georeferencing:ti,ab,kw OR "Global Positioning System":ti,ab,kw OR "Global Positioning Systems":ti,ab,kw OR Geofenc*:ti,ab,kw

Web of Science

Concept	Search Terms
Mobile applications	(ALL=((Smartphone) OR "Mobile Applications" OR smartphon* OR "mobile application*" OR "mobile app" OR "mobile apps" OR "mobile phon*"))
Geofencing	ALL=("Geographic Information Systems" OR "Geographic Information System" OR "Geographical Information System" OR "Geographical Information Systems" OR Georeferencing OR "Global Positioning System" OR "Global Positioning Systems" OR Geofenc*)

APA PsychINFO

Concept	Search Terms
Mobile applications	DE "Smartphones" OR DE "Mobile Applications" OR DE "Smartphone Use" OR DE "Text Messaging" OR DE "Wireless Technologies" OR DE "Mobile Phones" OR smartphon* OR "mobile application*" OR "mobile app" OR "mobile apps" OR "mobile phon*"
Geofencing	"Geographic Information System" OR "Geographical Information System" OR "Geographical Information Systems" OR "Georeferencing" OR "Global Positioning System" OR "Global Positioning Systems" OR Geofenc*

Appendix 2. **Details of nine studies that met inclusion criteria for the scoping review**

Name/citation Geofenced intervention Refernce number	Study characteristics	Development of geofence	Results	Theory and framework
Wright et al., 2021 Vendor not cited 41	*Study purpose:* Increase awareness and use of dental services in a rural clinic *Study design:* Pre and post intervention community and outcome assessments *Target population:* Residents of a rural zip code surrounding a dental clinic *Sample size:* 516,073 impressions delivered to individuals crossing the geofence *Duration of follow-up:* Impressions were sent over a 60-day period *Outcome of interest:* Number of impressions displayed to a user, clicks on the banner, click-through rates on the dental website from the banner, and pre/post intervention community knowledge of the dental clinic	*User input:* None *Mechanism of delivery:* Any individual with a smartphone physically located within the boundaries of three zip codes near the dental clinic received a geofence message advertising the dental clinic with webpage information for additional information	Over 60 days, 516,073 impressions were delivered, with 475 individuals clicks on the banner to get website information, and a click through rate of 0.09%. Increases were seen in community knowledge about the clinic (p=0.045) and dental visits by respondent or a family member (p=0.04) post intervention	*Theoretical framework:* Anderson Model of Health Services Use *Behavioral* *Social:* Informational support of an existing service that is place-based *Cognitive*

Owei et al., 2021 ResQ 44	*Study purpose:* Assess the impact of the ResQ geofencing app on submission rates for duty hours and number of violations reported *Study design:* Mixed methods feasibility and acceptability of the ResQ app. *Target population:* Residents from the General Surgery Residency Program *Sample size:* 23 *Duration of follow-up:* 60 days *Outcome of interest:* Comparison of reported and recorded work hours submitted and work hour violations (80 hours per week and continuous hours worked). Additionally, 13 participants participated in semi-structured interviews to understand acceptability and feasibility of ResQ.	*User input:* None *Mechanism of delivery:* Geofences were placed around clinical sites where residents worked. The ResQ application was installed on resident's work phones and recorded work hours based on entering and exiting the geofence.	The mean number of violations decreased significantly (p=0.04) and work hour submissions did not differ with the intervention (p=0.42). Compared to the previous year, reported violations significantly decreased (p<0.01). Participants found the application useful for recording and reporting clinical hours and eased administrative burden.	*Theoretical framework:* None listed *Behavioral* *Social* *Cognitive:* Sense of safety in capture and reporting of clinical hours
Gustafson et al., 2014 A-CHESS 46	*Study purpose:* Determine if a smartphone application to support recovery from alcohol use disorders reduced risky drinking days. *Study design:* Unmasked randomized clinical trial	*User input:* High-risk locations were identified by participants *Mechanism of delivery:* Study team geofenced user	Along with the geofenced intervention, A-CHESS was a mobile application that provided monitoring, information, communication, and support services from counselors. Overall the A-	*Theoretical framework:* Self-determination theory *Behavioral:* Warning messages sent in risky areas

	Target population: People with diagnosed alcohol dependence discharged from residential treatment *Sample size:* 349 *Duration of follow-up:* 8 months *Outcome of interest:* Risky drinking days in the previous 30 days	identified high-risk locations and sent alerts to the user's smartphone asking if they wanted to be there	CHESS group reported fewer risky drinking days at follow-up (p=0.003)	*Social:* Informational support with counselors *Cognitive:* Passive and real-time capture of information shared with counselors
Nguyen et al., 2017 Ginger.io 18	*Study purpose:* Evaluate the use of smartphone-based geofencing for tracking hospitalizations *Study design:* Remote and in-person arm validation of1 a mobile application that detected hospitalizations and length of hospitalization *Target population:* Remote- participants from the Health eHeart study with a smartphone In-person- Patients scheduled for electrophysiology and cardiac catheterization procedures. *Sample size:* Remote- 3,443; In person- 22	*User input:* None *Mechanism of delivery:* The app was programmed with all U.S. hospitals geofenced. A notification was sent to within 1 hour of leaving the hospital vicinity asking participants to confirm if they received medical care	Remote- The application detected 800 unique participants in a geofenced location with a positive predictive value between 65-78% based on how hospitalization was confirmed. Most common error in detection was the participant was a medical center employee. In person- Visits were detected in 17/22 with confirmed hospitalization. Mean visit duration was not correlated with actual hospital length of stay.	*Theoretical framework:* None listed *Behavioral* *Social* *Cognitive:* Sense of safety in provider knowing your hospitalization status

	Duration of follow-up: Remote- mean of 260 days; In person- Duration of their scheduled procedure *Outcome of interest:* Detection of hospitalization			
Naughton et al., 2016 Q Sense 20	*Study purpose:* Feasibility and acceptability of a mobile application using geofencing to deliver tailored place-based intervention messages *Study design:* Explanatory sequential mixed methods *Target population:* Tobacco smokers willing to set a quit date within 1 month *Sample size:* 15 in quantitative arm and 13 qualitative interviews *Duration of follow-up:* Pre-quit period (up to 1 month) and 2 weeks post-quit date *Outcome of interest:* 1) User engagement with app; 2) Assess app's location-sensing accuracy; 3) Feasibility of geofence mechanism; 4) Limitations of everyday use of app	*User input*: Geofences based on user habits and reports of smoking locations *Mechanism of delivery:* If a smoker reported smoking in the same proximity, the device created a geofence around that area with a radius of 100m. When a user entered the geofence for greater than 5 minutes a location-tailored support messaged was triggered	User engagement with the application varied from 60% of days pre-quit and 39% post-quit (52% excluding outliers). Geolocation was collected on 97% of smoking reports with high accuracy. A mean of 1.5 geofences were created per participant with 87% having at least one. 5/9 participants eligible to receive a geofenced triggered message received at least one. Environmental constraints and forgetfulness were common reasons for forgetting to engage with app. Participants were positive about the value of the geofenced support	*Theoretical framework:* Learning theory and taxonomy of smoking behavior change *Behavioral:* Coping and resilience regarding smoking triggers *Social* *Cognitive*

			and had no privacy concerns.	
Dorsch et al., 2020 LowSalt4Life 47	*Study purpose:* Effectiveness of the LowSalt4Life mobile app on maintaining a low sodium diet and controlling blood pressure *Study design:* Unblinded randomized control trial *Target population:* Adults diagnosed with hypertension and taking antihypertensive medication *Sample size:* 50 randomized *Duration of follow-up:* 8 weeks *Outcome of interest:* Changes in 24-hour dietary recall and sodium intake, urine sodium excretion, blood pressure	*User input:* Mixed. Geofences were created based on user input as well as from a predictive service when a participant entered a grocery store, restaurant, or home. *Mechanism of delivery:* Contextual adaptive messages were sent to participant's phones when entering a geofence, with messages linked to content in the mobile application	There was a significant decrease in sodium excretion (p=0.03) and decrease in sodium intake via 24 hour dietary recall (p=0.01) and in the App group vs no App groups. Blood pressure decreased by 1.7 mmHg in the App group compared to 0.7 in the no App, but the change was not significant (p=0.12).	*Theoretical framework:* Theory of Planned Behavior *Behavioral:* Dietary messages sent when participant is in areas where they would purchase/consume food *Social:* Informational support regarding which products and food choices had lower sodium in context of place *Cognitive*
DeFilippis et al., 2017 Position Health 43	*Study purpose:* Determine the feasibility of patients with ventricular assist devices care engagement with and feasibility of a geofencing notification system. *Study design:* Feasibility study with quantitative and qualitative measures	*User input:* None *Mechanism of delivery:* Geofences were drawn around emergency departments (ED)	The system was actIve on 4 occasions, each of which the participant confirmed they were at or near the hospital but were not seeking care. 1 patient	*Theoretical framework:* None listed *Behavioral* *Social*

	Target population: Adults with a ventricular assist device (VAD) *Sample size:* 21 *Duration of follow-up:* 6 months *Outcome of interest:* Proper detection of emergency department utilization by participant and satisfaction with mobile application.	across the U.S. Once the application detected that a participant approached an ED, a prompt was sent to their phone to confirm if they were seeking care at that hospital. If yes, another prompt asked the participant to confirm if the app could notify their VAD healthcare team. If 'yes' to both, a notification was sent to the covering provider's pager with participant name and contact.	reported seeking ED care but did not receive a ping. Most patients responded favorable to their impression of the application stating that it "gave them peace of mind."	*Cognitive*: Sense of safety to participants that emergency room and hospitalizations could alert their VAD provider regarding the need to coordinate care
Connor & Herzig, 2016 Stat! 45	*Study purpose:* Determine the feasibility and acceptability of a mobile application that allow automatic capture of work hours without manual employee input *Study design:* Feasibility study	*User input:* None *Mechanism of delivery:* Geofences were drawn around hospitals where the anesthesia group provided services.	Use of the geofencing application showed a significant correlation of early departures following late departures the previous day ($p<0.01$ in 73 of 91 occasions), and better dispersion of	*Theoretical framework:* None listed *Behavioral* *Social*

	Target population: Anesthesia providers in a private practice group *Sample size:* 198 *Duration of follow-up:* 12 months *Outcome of interest:* Equitable workload distribution, employee acceptance and uptake, and reduced dispersion of the amount of overtime worked by staff	When the provider enters a geofence, their time at the facility is continuously checked and reported to a central server. Reports were then used to inform future clinical responsibilities and overtime worked	working hours (p=0.002) compared to the previous year. Acceptance of the mobile application was slow to start but >95% in less than 1 year of roll out	*Cognitive:* Sense of security regarding equitable distribution of work based on geofenced data and capture of time working for billing purposes
Besoain et al., 2020 UBESafe 22	*Study purpose:* Prevent sexually transmitted infections (STIs) by sending preventive measures in risky situations *Study design:* Development and feasibility *Target population:* Men who have sex with men *Sample size:* Development-5; Feasibility- 4 *Duration of follow-up:* Development- 2 weeks; Feasibility- 1 month *Outcome of interest:* Development- functional testing to receive user feedback; Feasibility- try the UBESAFE system with all its functionalities	*User input:* Mixed. Hot zones were created by a system administrator and with input from users *Mechanism of delivery:* Geofenced hot zones are areas demines with a high probability for intercourse. When users enter a hot zone, a contextual message to prevent HIV and STIs, and promote testing	All users triggered a geofenced hotzone during the development phase, though this was not quantified further. Hot zones were seen as a necessary component from those testing in the development phase. In the feasibility phase, users tested and rated prevention messages as well as adding their own. Users also contributed to hot zones and tested existing ones, contributing	*Theoretical framework:* Elaboration likelihood model *Behavioral:* Contextual messages for sexual risk reduction sent in hot spots for high-risk intercourse *Social:* Gamification of preventive messages and interaction with

			65% of hot zones in the application at the end of the study.	others using the application *Cognitive*

Appendix 3. **Components of mobile health evidence reporting and assessment.**									
	Wright et al., 2021	Owei et al., 2021	Gustafson et al., 2014	Nguyen et al., 2017	Naughton et al., 2016	Dorsch et al., 2020	DeFilippis et al., 2017	Connor & Herzig, 2016	Besoain et al., 2020
Infrastructure	■	■	■	■	■	■	■	■	■
Technology platform	■	■	■	■	■	■	■	■	■
Interpretability/Health information systems context		■					■	■	
Intervention delivery	■	■	■	■	■	■	■	■	■
Intervention content	■	■	■	■	■	■	■	■	■
Usability/content testing					■		■	■	■
User feedback		■		■	■		■	■	■
Access of individual participants		■	■	■	■		■	■	■
Cost assessment	■		■						
Adoption inputs/program entry	■	■	■	■	■	■	■	■	■
Limitations for delivery at scale		■		■	■				
Contextual adaptability					■				
Replicability			■			■	■	■	■
Data security							■	■	
Compliance with national guidelines or regulatory statutes									

Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Checklist

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
TITLE			
Title	1	Identify the report as a scoping review.	
ABSTRACT			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	
METHODS			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.	
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	
Information sources*	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	
Selection of sources of evidence†	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	
Data charting process‡	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	
Critical appraisal of individual sources of evidence§	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
RESULTS			
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	
DISCUSSION			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	
Limitations	20	Discuss the limitations of the scoping review process.	
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	
FUNDING			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	

JBI = Joanna Briggs Institute; PRISMA-ScR = Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews.

* Where *sources of evidence* (see second footnote) are compiled from, such as bibliographic databases, social media platforms, and Web sites.

† A more inclusive/heterogeneous term used to account for the different types of evidence or data sources (e.g., quantitative and/or qualitative research, expert opinion, and policy documents) that may be eligible in a scoping review as opposed to only studies. This is not to be confused with *information sources* (see first footnote).

‡ The frameworks by Arksey and O'Malley (6) and Levac and colleagues (7) and the JBI guidance (4, 5) refer to the process of data extraction in a scoping review as data charting.

§ The process of systematically examining research evidence to assess its validity, results, and relevance before using it to inform a decision. This term is used for items 12 and 19 instead of "risk of bias" (which is more applicable to systematic reviews of interventions) to include and acknowledge the various sources of evidence that may be used in a scoping review (e.g., quantitative and/or qualitative research, expert opinion, and policy document).

From: Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA Extension for Scoping Reviews (PRISMAScR): Checklist and Explanation. Ann Intern Med. 2018;169:467–473. doi: 10.7326/M18-0850.