Helping people see their place in community immunity: a dynamic web-based visualization

Thèse

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HELPING PEOPLE SEE THEIR PLACE IN COMMUNITY IMMUNITY: A DYNAMIC WEB-BASED VISUALIZATION

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Résumé

L'immunité collective - parfois appelée immunité de groupe - est un concept important et complexe de la santé publique qui n'est pas toujours bien compris par le grand public. Cette incompréhension est particulièrement prononcée chez les personnes qui hésitent à se faire vacciner.

Des recherches antérieures ont suggéré que la décision d'obtenir un vaccin pour soi ou son enfant est principalement motivée par les avantages et les risques individuels, plutôt que par les avantages pour la communauté. Cependant, peu de recherches ont identifié des moyens d'aider les gens à comprendre le fonctionnement de l'immunité collective. Il y a également eu relativement peu de recherches sur le rôle des émotions sur la perception du risque et sur les connaissances et les comportements relatifs à l'immunité collective. La visualisation d'informations est un mécanisme de communication puissant pour transmettre des informations et des données sur les risques, car elle permet de présenter rapidement des concepts complexes de manière claire et attrayante. La visualisation d'informations pourrait également permettre d'influencer les émotions.

La première partie de ce travail visait à examiner systématiquement les interventions conçues pour communiquer au grand public ce qu'est l'immunité collective et comment elle fonctionne. Cet examen systématique a montré qu'il existe relativement peu de preuves scientifiques des effets de stratégies de communication sur l'immunité collective. Il existe un certain nombre d'interventions disponibles en ligne pour transmettre le concept d'immunité collective, mais leurs effets ont rarement été évalués et aucune étude n'a évalué les effets des interventions sur les émotions.

La deuxième partie de ce travail visait à concevoir une application Web au sujet de l'immunité collective et à optimiser cette application en fonction des réponses cognitives et émotionnelles des utilisateurs. Dans notre application, les utilisateurs sont invités à construire leur communauté en créant un personnage qui les représente (leur avatar) et huit autres personnages qui représentent des personnes de leur entourage, par exemple leur famille ou leurs collègues de travail. L'application intègre ces personnages dans une visualisation animée de deux minutes montrant comment différents paramètres (par exemple, la couverture vaccinale et les contacts au sein des communautés) influencent l'immunité collective. Cette étude a montré que notre animation avec des avatars personnalisés peut aider les gens à

comprendre leur rôle dans la santé de la population. Notre application s'est révélée être une méthode de communication prometteuse pour expliquer la relation entre les comportements individuels et la santé de la communauté. Elle offre une stratégie potentielle pour concevoir du matériel de communication sur des sujets complexes tels que la santé ou l'immunité collective.

La troisième et dernière partie de ce travail visait à évaluer les effets de notre application Web montrant le fonctionnement de l'immunité collective sur la perception des risques, sur les émotions, sur la confiance dans les informations, sur les connaissances et sur les intentions en matière de vaccination. Dans le cadre d'un vaste essai contrôlé randomisé en ligne et factoriel, notre application a influencé tous les résultats dans le sens souhaité, en particulier chez les personnes ayant une vision du monde plus collectiviste. Cette étude est encore plus pertinente aujourd’hui, alors que les pays du monde entier mènent des campagnes de vaccination contre la COVID-19. Notre application est d'ailleurs présentement utilisée dans un outil d'aide à la décision en ligne, permettant aux gens de prendre une décision éclairée par rapport aux vaccins contre la COVID-19 pour eux-mêmes ou leurs enfants.

Abstract

Community immunity—sometimes referred to as herd immunity—is an important and complex concept in public health that is not always well-understood by members of the general public. This lack of understanding is particularly pronounced among people who are vaccine hesitant.

Previous research has suggested that decisions about whether or not to vaccinate oneself or one's child are primarily driven by benefits and risks to the individual, with community-level benefits being less compelling. However, little research has identified ways to help people understand how community immunity works, and there has also been relatively little research investigating the role of emotion in risk perceptions, knowledge, and behavior relevant to community immunity. Visualization is a powerful communication mechanism for communicating information and data, including information and data about risk, because it enables rapid presentation of complex concepts in understandable, compelling ways. Visualization may also influence emotions.

The first part of this work was aimed to systematically review interventions designed to communicate what community immunity is and how community immunity works to members of the general public. This systematic review demonstrates that there is relatively little evidence about the effects of communicating about community immunity. There are a number of interventions available online for conveying the concept of community immunity, but very few interventions were evaluated for its effects and no studies evaluated the effects of interventions on emotions.

The second part aimed to design a web application about community immunity and optimize it based on users' cognitive and emotional responses. In our application, people build their own community by creating an avatar representing themselves and 8 other avatars representing people around them, for example, their family or coworkers. The application integrates these avatars in a 2-min visualization showing how different parameters (eg, vaccine coverage, and contact within communities) influence community immunity. This study found out that applications with personalized avatars may help people understand their individual role in population health. Our application showed promise as a method of communicating the relationship between individual behaviour and community health. It offers a potential roadmap for designing health communication materials for complex topics

such as community immunity.

The third and last part of this work aimed to evaluate the effects of our online application showing how community immunity (herd immunity) works on risk perception, emotions, trust in information, knowledge and intentions regarding vaccination. In a large, factorial, online randomized controlled trial, our application influenced all outcomes in the desired directions, particularly among people who have more collectivist worldviews. This work is increasingly relevant as countries around the world carry out COVID-19 vaccination campaigns. Accordingly, our application is currently being used in an online decision aid to support people making evidence-informed decisions about COVID-19 vaccines for themselves or their children.

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Abbreviations

1. MMAT, Mixed method assessment tool
2. SD, Sample standard deviation
3. MMR, Measles Mumps and Rubella
4. IB, Individual Benefits
5. SB, Social Benefits
6. Ctl,Control
7. EEG: electroencephalogram
8. OSF Open Science Framework
9. (IQR) Interquartile range
10. CI, Confidence interval
11. Df, Degree of freedom
12. p, p-value
13. F, F-statistic
14. LR Chisq, Likelihood ratio tests
15. ANOVA, Analysis of variance

Dedication

To my late parents, who have supported me in all my personal and academic endeavors. Ami, thank you for believing in me and encouraged me to not give up and to achieve the highest degree possible. The promise I made to you has helped me to pass all hurdles in life and to pursue this PhD Degree. Daddy, thank you for being a wonderful dad and sparking my interest in the healthcare field. I have learned so much from you throughout my life. I saw how professional and passionate you were to help others which pushed you to be the best that you could be. I hope to have that same drive in my career. You both have inspired me to be a better human being.

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My sincere thanks go to Daniel Reinharz, Professor at the Department of Social and Preventive Medicine of Medicine Faculty, at Laval University, co-director of my thesis. Thank you for giving me the chance to enter the PhD program in Canada. Your support and standing by me through my hardest initial years of my PhD are anchored in my memory. Even though you were working then in Laos, you always kept in touch with me and wanted to know my progress. You have given me hope in the moments when I had none. It is a privilege and a great opportunity to be working with you. I thank you for your support, and your words of encouragement, for which I am forever grateful to you.

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Finally, my thoughts go to the people (especially women and children) of my city Peshawar located in the northwestern region of Pakistan. Surviving uncertain and difficult times, with courage and dignity, may this work bring hope and the desire to learn more and reach the stars.

Preface

The dynamic relationships between individual- and population-level behaviors and outcomes are at the heart of public health. Based on these dynamics, immunization has proven its effectiveness in immunization programs and reduces the risk of vaccine preventable diseases by extending vaccine benefits in the form of herd immunity. 'Herd immunity' or 'community immunity' refers to the reduced risk of infection among susceptible individuals in a population through the presence and proximity of immune individuals. Previous research has suggested that people make decisions about vaccines influenced more by individual-level potential benefits and harms. However, it is not clear whether community-level benefits are well-understood but simply not important to people, or whether community-level benefits lack influence in individual decisions because such benefits are not well communicated. The objective of this dissertation was first to review the evidence regarding communicating how community immunity works. The next step was to develop a web-based application containing a visualization to help people to understand the concept of community immunity, including how it safeguards vulnerable people who cannot be vaccinated; for example, because they are either too young, or old, or have fragile immune systems. The final step was to evaluate the application's effects on risk perception, vaccination intentions, trust in information, emotions, and knowledge among members of the general public. This work is supervised by Professor Holly Witteman (PhD) and co-supervised by Professor Daniel Reinharz (MD, PhD).

This thesis has eight chapters and resulted in two published articles and six presentations. Presentations occurred at two national conferences (Canadian Immunization Conference) and four international conferences (International Shared Decision Making, Society for Medical Decision Making) related to the topic of study.

The first included published article is entitled "Interventions to help people understand community immunity: A systematic review." It was published in the journal Vaccine in January 2019. Specifically, tables, figures, and appendices are renumbered, and where appropriate, I changed instances of 'we' to 'I' to emphasize the portions of the work I personally conducted compared to portions I led with contributions from other team members. I was the first author of this paper. With input from our co-authors, I and my supervisor designed the study, planned the data collection, conducted data analysis and interpretation, and drafted the manuscript. All co-authors critically revised multiple iterations of the manuscript and approved the final version for submission for publication. This was the first paper of my doctoral work, and my role in this paper was to lead the work and the writing with the support and guidance of my supervisor. The authors for this article were: Hina Hakim, Thierry Provencher, Christine T Chambers, S Michelle Driedger, Eve Dubé, Teresa Gavaruzzi, Anik M C Giguere, Noah M Ivers, Shannon MacDonald, Jean-Sebastien Paquette, Kumanan Wilson, Daniel Reinharz, and Holly O Witteman.

The second included published article is entitled “A Web Application About Herd Immunity Using Personalized Avatars: Development Study.” It was published in the Journal of Medical Internet Research in May 2020. There are minor differences between the published article and the associated chapter in this thesis. Specifically, tables, figures, and appendices are renumbered, and where appropriate, I changed instances of ‘we’ to ‘I’ to emphasize the portions of the work I personally conducted compared to portions I led with contributions from other team members. I was the first author of this paper. With input from our co-authors, I and my supervisor designed the study and conducted data analysis and interpretation. I then drafted the first version of the manuscript and incorporated multiple rounds of revisions and comments from my supervisor and co-authors. All co-authors critically revised multiple iterations of the article and approved the final version for submission for publication. This was the second paper of my doctoral work, and my role in this paper was to lead the work and the writing with the support of my supervisor. The authors for this article were: Hina Hakim, Julie A Bettinger, Christine T Chambers, S Michelle Driedger, Eve Dubé, Teresa Gavaruzzi, Anik M C Giguere, Éric Kavanagh, Julie Leask, Shannon E MacDonald, Rita Orji, Elizabeth Parent, Jean-Sébastien Paquette, Jacynthe Roberge, Beate Sander, Aaron M Scherer, Martin Tremblay-Breault, Kumanan Wilson, Daniel Reinharz, Holly O Witteman.

Introduction

Many vaccines protect against disease by not only preventing infection in those receiving the vaccine but also preventing the infection from being transmitted from one person to another (Metcalf et al., 2015; Rashid et al., 2012). The term community immunity, also known as herd immunity, refers to the indirect protection of unvaccinated people by elevating the level of immunity among those who can be immunized. Such an elevation breaks the chain of transmission and decreases the overall probability of contact with an infectious agent, thereby preventing the spread of infectious agents within susceptible populations (Rashid et al., 2012).

Community immunity can be a complex concept to convey. Whether or not a given population achieves community immunity depends on many variables, including vaccine effectiveness and coverage, whether or not susceptible individuals form clusters, timing of vaccine administration, and the presence or absence of serotype replacement (Scarbrough Lefebvre et al., 2015). Perhaps as a result, people can easily fail to understand the connection between individual-level vaccination behaviour and community-level risk (Downs et al., 2008).

Vaccine hesitancy refers to, "delay in acceptance or refusal of vaccines despite availability of vaccine services" (MacDonald, 2015). Vaccine hesitancy is a complex and context-specific problem which depends on several social, cultural, religious, philosophical, and emotional factors (Dubé, Gagnon, et al., 2015). Vaccine hesitant communities who are clustered geographically or that share a set of philosophical or cultural beliefs avoid vaccination, (Omer et al., 2009; Salathé & Bonhoeffer, 2008) and therefore put themselves and communities around them at greater risk for contracting vaccine preventable diseases (Leslie et al., 2018). Research has shown that even if there are high levels of vaccine coverage at national, regional and local levels, there can still be localized clusters of low vaccine uptake (Delamater et al., 2016; Glasser et al., 2016; Lieu et al., 2015; P. J. Smith et al., 2015). The existence of such clusters puts surrounding communities at risk of infection (Sugerman et al., 2010).

Many public health interventions, including those addressing vaccine hesitancy (Dubé, Gagnon, et al., 2015), are based on an "information deficit model" (Simis et al., 2016) assuming that individuals will change their behaviour if provided with more information to increase their knowledge. Knowledge is a first step, but not enough to make a behaviour change (K. Corace & Garber, 2014). Research has shown that vaccine hesitancy is a complex problem (Dubé et al., 2013). Despite the success of vaccines and immunization programs as public health measures yet, some people may perceive such measures as unsafe or even unnecessary (Alfredsson et al., 2004; Dube et al., 2012). The reasons behind such perceptions include concerns about vaccine safety, a mistrust in healthcare agencies or pharmaceutical companies, inaccurate mental models, and unfamiliarity with vaccine-preventable diseases (Downs et al., 2008; Omer et al., 2009; Salmon et al., 2015; L. E. Smith et al., 2017).

Poor communication about the merits of vaccines and how they work can be a contributing factor to vaccine refusal (Leask et al., 2012). The way information is communicated has an influence on people's decision-making process. Logan and colleagues suggest that providing education about community immunity and vaccination coverage could be useful for increasing willingness to vaccinate, generating benefits both to individuals and communities (Logan et al., 2018). However, few interventions exist to specifically convey the concept of community immunity (Betsch et al., 2013, 2017; Vietri et al., 2012). Given the difficulty in understanding the concept of community immunity, it is plausible that its lack of observed influence on decisions may stem partly from a lack of clarity about the concept. Furthermore, previous research in this domain has rarely considered the role of emotions—this, despite the known ways in which communication methods can influence emotions and in which emotions, in turn, drive risk perceptions and decision making (G. F. Loewenstein et al., 2001; G. Loewenstein & Lerner, 2003).

Visualization is a powerful communication mechanism that uses pre-attentive processing to communicate large amounts of information rapidly in understandable and compelling ways (Costa et al., 2020). At the outset of my doctoral work, little visualization research had addressed the challenge of communicating the complex concept of community immunity.

In my doctoral work, I aimed to develop and evaluate a dynamic visualization conveying the concept of community immunity. To achieve this, I first systematically reviewed the literature to identify previous efforts to convey the concept of community immunity and their effectiveness. Secondly, I iteratively developed an application incorporating visualization explaining how community immunity works, and lastly, I evaluated the developed visualization in an online experiment to assess its effects on risk perception (to an individual and those around them), emotions, attitudes, beliefs, and behavioral intentions.

Chapter 1: Literature review

1.1 Community immunity

1.1.1 Definitions and terminology

Authors have defined the idea of community-level indirect protection in different ways. Terms in use include: herd protection, herd effect, herd threshold, community protection, and community immunity. There is no clear consensus as to how the concept itself should be defined (Gonçalves, 2008).

The term herd immunity was first coined in 1923 by Topley and Wilson. During their research on epidemics in laboratory mice, they proposed that immunity is an attribute of the herd. In addition, they suggested that the concept of herd immunity could be used to better understand infections in human populations (S. A. Plotkin et al., 2008). Later on, Fox and colleagues (1971) used a definition for herd immunity taken from the 1965 edition of the Dorland Medical Dictionary, which defined the concept as "the resistance of a group to attack by a disease to which a large proportion of the members are immune, thus lessening the likelihood of a patient with a disease coming into contact with a susceptible individual." The idea was further explored by Reed and Frost and later by their students through mathematical modelling (de Maia, 1952). In 1990, Anderson used the concept of a "herd immunity threshold" to define herd immunity as a process that affects population-level immunity (Anderson, 1992). He proposed that the herd immunity threshold is dependent on ecological factors that determine whether a community can grow large enough to sustain the transmission of infectious agents. Subsequently, John and Samuel (2000) introduced a new term, herd effect, to denote, "the incidence of disease or infection in an unimmunized population, induced by herd immunity or immunization." Kim and colleagues (2011) would later use the terms herd effect and herd immunity synonymously, defining them as an indirect form of protection given by vaccinated groups to unvaccinated individuals. In their book "Vaccines", Plotkin and colleagues (2008) replaced the term herd immunity with a new term: community immunity, which they define as the way in which a given level of immunity (vaccination and antigen-antibody reaction) is distributed within a community.

Thus, over the course of almost a century, different terms were introduced to express the idea of herd immunity. Some authors tended to favour one definition over another, while others used different terms interchangeably. Gonçalves (2008) reviewed the various definitions and summarized the debate by explaining that herd immunity is an indirect protection given by vaccinated members to unvaccinated individuals in a given community. Therefore, vaccination can be thought of as a prosocial act (Korn et al., 2020).

In this work, I adopt Halsey and Salmon's definition of herd immunity as a form of community immunity (Halsey & Salmon, 2015). The term broadens the notion of prosocial acts to include both vaccines and the natural rendering of disease-induced benefits. Through the rest of this proposal, I will use the term community immunity to refer to the way in which individuals, having become immune to a disease through illness or vaccination, provide indirect protection to other members of the population who remain susceptible to the disease. As such, the notion of community immunity can be thought of as a collective property of the community.

1.1.2 How community immunity works

Community immunity reduces the spread of infection because when a sufficient proportion of the population is immune to a disease, either through natural or induced immunity, it is unlikely that the disease will circulate. Widespread community immunity has helped eradicate vaccine-preventable diseases. For example, smallpox was eradicated[1] worldwide in the 1970's and there are promising signs that polio and diphtheria can be controlled (Rashid et al., 2012). The indirect protection derived from community immunity also means that, in cases of infectious disease outbreaks, there may be no need to vaccinate the entire population when vaccinating a portion of the population will be sufficient to protect the community and reduce the transmission of infectious agents. For example, in the 1990s, Japan controlled an influenza outbreak in the elderly by vaccinating school children (Reichert et al., 2001).

[1] *Eradication*: Permanent reduction to zero of the worldwide incidence of infection caused by a specific agent as a result of deliberate efforts; intervention measures are no longer needed. *Control*: to mean reduction of disease incidence, prevalence, morbidity, and/or mortality to a locally acceptable level as a result of deliberate efforts (Who, 2015).

Community immunity depends crucially on the dynamics of individual immunity. When a person becomes infected, it increases the risk that other individuals will also contract the illness. At the same time, the infected person will develop a long-term immunity to the disease, which will reduce the number of individuals susceptible to catching the infection. Consequently, if the proportion of the population that is immune increases, either through vaccination or natural immunity, then the incidence and spread of the disease will decline in the community.

A fundamental parameter of community immunity is the basic reproductive number (R_0), which represents the number of new infections generated by the first person to be infected in a given population. R_0 does not account for the new incidence of the disease produced by secondary cases. It does, however, include those who were exposed to the first infected individual but did not become infectious themselves (Halloran, 1998). The number R_0 is expressed in equation form as:

$$R_0 = cpd$$

Where c is the number of contacts per unit time, p is the probability of transmission is defined as the likelihood of a successful transfer of infectious agent, given contact between an infection and the host, and d is the duration of infectiousness (Halloran, 1998).

This formula assumes that all contacts can lead to infection, whereas, in reality, some individuals will already be immune to the infectious disease in question. If so, the expected number of new cases will be less than R_0. This expected number is denoted by R_t, R_e or R and is referred to as the effective reproductive number (D. Adam, 2020). The effective reproductive number is the product of the basic reproductive number (R_0) and the proportion of contacts (x) that could lead to infection (Halloran, 1998). In their theoretical work, Fine and colleagues (2011) use the concept of the herd immunity threshold to explain herd immunity and address some of the complexities surrounding community immunity. The authors suggest that, to eradicate a disease (i.e., to lower the incidence of infection), the number of immune individuals in a given population must be equal to or greater than the critical rate of vaccine coverage (Vc) expressed in equation form as $Vc = (1 - \frac{1}{\mathrm{R0}})/\mathrm{E}$. In this formula, E denotes the vaccine's effectiveness in fighting the transmission of the disease.

Consequently, if the effectiveness of the vaccine is less than $(1 - \frac{1}{R0})$, it will be difficult to reduce the rate of transmission. Moreover, the extent of vaccination coverage required depends crucially on risk behaviour. Specifically, groups within communities that interact more with each other will require greater vaccination coverage since they tend to have higher R_0 values and are more prone to the spread of infections. Indirect protection is compromised, and infections are more likely to spread when such high-risk groups are not vaccinated and allowed to mix homogeneously with unimmunized segments of the population. Another factor which may influence herd immunity is the presence of individuals who benefit from indirect protection without contributing to it (P. Fine et al., 2011). Under such a scenario, individuals who are vaccinated or become immune by contracting an infection provide indirect protection to the rest of the community, including those who are then able to use this protection instead of being vaccinated. As such, community immunity may erode if the number of people who are unvaccinated increases. This increase in unvaccinated members of the population can result in outbreaks of infectious diseases (Rashid et al., 2012).

1.1.3 Determinants of community immunity

The degree to which an infection can spread has important implications for vaccination coverage. A certain level of vaccine coverage is necessary to maintain the threshold required for community immunity. Therefore, the widespread presence of immune individuals within a community is important to prevent the transmission of diseases and to attain community immunity (Donaghy et al., 2006; P. Fine et al., 2011; Plans-Rubió, 2012). Each type of infection has a different threshold to confer community immunity and therefore a different level of necessary vaccine coverage (Donaghy et al., 2006; P. Fine et al., 2011). Community immunity works best when susceptible people and those who contracted the infection mix homogeneously across the population and thus influence the required threshold (Scarbrough Lefebvre et al., 2015). The factors that influence community immunity are: (1) Vaccine effectiveness; (2) Vaccine coverage; (3) Distribution patterns of infection among populations; (4) Timing of vaccine administration; and (5) Serotype replacement.

1.1.4 Vaccine effectiveness:

Vaccine effectiveness refers to the ability of vaccines to protect against infection in real-world situations. This is different from the concept of vaccine efficacy, which denotes the percentage reduction in the incidence of disease within a vaccinated group compared to an unvaccinated group under controlled conditions such as those observed in clinical trials. The effectiveness of a given vaccine may vary between regions, populations, and communities (Plans-Rubió, 2012). Moreover, vaccines are never completely effective (P. Fine et al., 2011; Plans-Rubió, 2012). Some vaccines' effectiveness wanes over time (e.g., measles, mumps, pertussis), which can reduce community immunity. In such cases, maintenance of immunity can be achieved by administering booster shots or through natural exposure to the infection (Scarbrough Lefebvre et al., 2015).

1.1.5 Vaccine coverage:

Vaccine coverage refers to the percentage of people who receive a vaccine in relation to the overall population. Community immunity is more likely to be achieved when vaccine coverage is high (Scarbrough Lefebvre et al., 2015). Low rates of vaccine coverage weaken community immunity and can lead to outbreaks of disease. For example, between 1989 and 1990, a measles outbreak in the United States occurred among children of minority ethnic groups with low rates of vaccine coverage (Bogaards et al., 2011). Similarly, low vaccine coverage and low community immunity increased the incidence rate of measles in the European Union in 2017- 2018 (Plans-Rubió, 2019). Sustaining a critical level of vaccination coverage thus helps to maintain indirect protection against infections (P. Fine et al., 2011).

1.1.6 Distribution patterns of infection among populations:

Unvaccinated individuals are more likely to become infected when pockets or clusters of susceptible individuals are formed (Donaghy et al., 2006; P. Fine et al., 2011; Salathé & Bonhoeffer, 2008), increasing a community's susceptibility to infection (Barskey et al., 2009; Donaghy et al., 2006; Salathé & Bonhoeffer, 2008). Clustering can occur due to involuntary grouping (e.g., schools and prisons) or through voluntary social groups who share similar religious or philosophical beliefs about vaccination. When individuals who oppose or are hesitant towards vaccination form social clusters, there is a higher likelihood of disease outbreaks (Dallaire et al., 2009; Onnela et al., 2016; Salathé & Bonhoeffer, 2008). Such increased likelihood may help explain why outbreaks of disease occur even in countries with overall high rates of vaccination coverage (Phadke et al., 2016; Salathé & Bonhoeffer, 2008; Truelove et al., 2019). Fortunately, despite the challenges posed by clustering, targeting reservoirs of infection can still induce community immunity and lower the transmission of infections even if there is some degree of social clustering by people opposed to vaccines (Scarbrough Lefebvre et al., 2015). Most vaccination programs aim at reducing the number of potential infections in a population (Bauch & Earn, 2004). To this end, special attention is given to vaccinating children, the elderly, and socially marginalized groups, since they are often at greater risk for infection. Delaying or refusing vaccination puts these segments of the population—as well as the rest of the community—at risk (Omer et al., 2009).

1.1.7 Timing of vaccine administration:

Timing is another important determinant of community immunity. Specifically, vaccine effectiveness depends on both the timing and timeliness of administration. For example, a Swiss study demonstrated that the timing and timeliness of measles immunizations influence a child's susceptibility to the disease (Bielicki et al., 2012). Children become susceptible to measles six months after birth when maternal antibodies begin to fade. Bielicki and colleagues (2012) concluded that any delay in administering the measles vaccine would increase the likelihood of infection.

1.1.8 Serotype replacement:

Another factor that affects community immunity is serotype replacement, which refers to the emergence of new disease-causing serotypes that are not targeted by existing vaccines (H. J. Adam et al., 2010). For example, since the introduction of a pneumonia vaccine, other serotypes of pneumonia have replaced the ones in the vaccine (Weinberger et al., 2011). Community immunity is compromised when the vaccines developed no longer target the correct strain (serotype). For example, an increase in the incidence of haemophilus influenza occurred when the relevant serotype was not covered by the existing vaccine (H. J. Adam et al., 2010). Fortunately, influenza vaccination is still effective in preventing pediatric hospitalization during most seasons (Buchan et al., 2017). Concerns about serotype replacement have been much-discussed during the COVID-19 pandemic, as existing vaccines may be less effective against variants of concern than they were against the original strain of SARS-CoV-2, the virus causing COVID-19 (Bian et al., 2021; Madhi et al., 2021; Rubin, 2021).

In summary, when individuals are immune to a disease, either because of natural illness or vaccination, they provide indirect protection to community members who remain susceptible to the disease. The next section discusses the challenges associated with delaying or refusing vaccination and its effect on community immunity and the likelihood of disease outbreaks.

1.2 Vaccines

1.2.1 Historical background of vaccine development

Vaccination is the deliberate attempt to protect humans against infectious disease. Vaccines were first developed in the 18th century when the first vaccine was discovered by Edward Jenner and a farmer, Benjamin Jesty. They had noticed that milkmaids were protected from smallpox and concluded that it was due to their exposure to cowpox (Stanley A. Plotkin & Plotkin, 2011). Jenner would go on to carry out trials and publish his results (Jenner, 1798). The virus, which Jenner called vaccinia, was later used to create a vaccine that eventually contributed to the elimination of smallpox. Jenner's work was followed by Louis Pasteur's discovery of *Pasteurella multocida* in chickens suffering from cholera, which spawned the production of an attenuated form of bacterium. Through his subsequent research on rabies and anthrax, Pasteur was able to produce the first attenuated vaccines, a discovery which revolutionized both science and medicine (Stanley A. Plotkin & Plotkin, 2011).

Towards the end of the 19th century, outbreaks of yellow fever in Africa led to the creation of a vaccine made with the yellow fever virus strain 17D. The subsequent vaccination campaign undertaken to contain the illness was a major success (Lloyd et al., 1936; Theiler & Smith, 1937). Around the same time, two additional vaccines, one for Bordetella pertussis and the other for influenza, made remarkable breakthroughs by demonstrating that vaccines induce immunity prior to infection (W. Smith et al., 1933).

During the last decade of the 19th century, major work was undertaken to develop vaccines by researchers from Great Britain, Germany, the United States, and France's Pasteur laboratory. It was during this period that Daniel Salmon and Theobald Smith discovered how to inactivate bacteria, which led to the development of vaccines for typhoid, cholera, and the plague (Stanley A. Plotkin & Plotkin, 2011). The concept of the serum antibody was developed by Emil von Behring, Shibasaburo Kitasato, Émile Roux, Alexandre Yersin, Almwroth Wright, and Paul Ehrlich. In 1888, Roux and Yersin established that diphtheria bacilli produces an exotoxin, and later von Behring and Kitasato identified the role antitoxins play in stimulating an immune response. This allowed Ehrlich to expand the concept of immunity to include antigen-antibody complexes (Stanley A. Plotkin & Plotkin, 2011). In 1923, Alexander Glenny and Barbara Hopkins studied diphtheria toxin and succeeded in converting it into a toxoid using formalin. Subsequently, a stable, non-toxic, formalin-inactivated diphtheria antigen was produced by Gaston Ramon. Albert Calmette and Camille Guérin from the Pasteur Institute also developed the Bacillus Calmette-Guérin (BCG), a vaccine against tuberculosis, which was first used in 1921 (P. E. M. Fine et al., 1999).The middle part of the 20th century saw the development of several important vaccines. During the 1960s, attenuated vaccines for measles, mumps and rubella (MMR) were created (Hilleman et al., 1968; Katz, 1960; Meyer & Parkman, 1971; S. A. Plotkin et al., 1969; Prinzie, 1969). This was followed by the development of a vaccine for the varicella zoster virus (Takahashi et al., 1975). Since vaccines induce antibody and cellular immune responses to viruses that are similar to what occurs naturally, their efficacy was predictable. Subsequently, vaccines against typhoid, hepatitis A and rabies were developed (Stanley A. Plotkin & Plotkin, 2011).

1.2.2 How vaccination works

Immunity is the ability of the human organism to tolerate the presence of materials indigenous to the body (self) and to eliminate foreign materials (non-self). In this way, the immune system helps protect the body against various infectious diseases. There are two types of immunity: passive immunity and active immunity. Passive immunity refers to the transfer of antibodies from one person (or non-human animal) to another. For example, the transfer of antibodies during pregnancy from mother to child through the placenta provides infants with temporary protection (Atkinson et al., 2011). On the other hand, active immunity consists of stimulating the immune system to produce antigen-specific humoral immunity (antibodies) and cellular or cell-mediated immunity. Active immunity can last for several years and sometimes for life. One way to acquire it is by contracting and eliminating an infection; the other method is through vaccination.

Vaccination implies deliberately introducing an antigen to provoke an immune response. Vaccines interact with the immune system to produce an active immunity similar to the immunity produced by natural infection, but without causing the disease and its potential complications. The primary purpose of the immune system is to identify foreign substances (antigens) in the body. Antigens can be live substances, such as viruses and bacteria, or inactivated materials capable of producing an immune response. The body develops a defense mechanism by using antibodies or immunoglobulins (protein molecules produced by B lymphocytes) to eliminate the foreign substances. Generally speaking, vaccination does not cause illness, but rather, stimulates the immune system into producing T-lymphocytes and antibodies (Atkinson et al., 2011). Once the simulated infection goes away, the body is left with memory T-lymphocytes and B-lymphocytes, which will fight even more effectively against the same pathogen if a person is re-infected. Many vaccines deliver a dead or attenuated pathogen, which allows the immunologic memory to stimulate an immune response if or when a person becomes infected with the real pathogen (Atkinson et al., 2011). Although the most effective immune responses are generally produced in reaction to a live antigen resulting from infection, effective immune responses can also be produced through vaccination (Atkinson et al., 2011), typically within a few weeks after a vaccine has been administered.

1.2.3 Vaccine concerns and anti-vaccine movements

Over the last century, vaccines have played an important role in improving public health. However, ever since their introduction, there has been public concern over their safety and effectiveness. Negative attitudes towards vaccines can become an issue if they result in a breakdown of community immunity.

Concerns over vaccines date back to the 18th century when a smallpox epidemic hit the United States. Edward Jenner had demonstrated that infecting a person with cowpox blisters could protect them from smallpox. As a result, individuals in the United States who received the vaccine had higher survival rates compared to the rest of the population. Nevertheless, opposition to vaccines began to grow. The anti-vaccine movement was led by Dr. William Douglass and James Franklin (the older brother of Benjamin Franklin, one of the founding fathers of the United States). Some opponents believed vaccination was a violation of the natural order and interfered with God's will (Boom & Cunningham, 2014). There were also fears that vaccines were unsafe. In England, the anti-vaccine movement was born in 1866 after the British government implemented a mandatory public vaccination plan (Boom & Cunningham, 2014). The opposition to vaccines was led by Richard Butler Gibbs, an Irish homeopath, his brother George, and their cousin John Gibbs. While the anti-vaccine campaign was highly effective in England, it had very little effect in Scotland and Ireland, where people were less resistant to vaccination. These differences in attitudes may explain why the rate of smallpox in England was much higher at the time compared to Scotland and Ireland (Offit, 2011).

Concerns about vaccine safety are not without cause. For example, in 1955, a batch of polio vaccine was produced by the Cutter Laboratory in Berkeley, California. The batch was not fully inactivated, with tragic results: 70,000 children were infected with mild symptoms of polio, 200 were paralyzed and 10 died. Following the incident, many people became fearful of vaccines and distrustful of pharmaceutical companies (Offit, 2005, 2011).

During the 20th century, the anti-vaccine movement gained new momentum when, in 1982, NBC aired a documentary called "DPT: Vaccine Roulette," written and produced by Lea Thompson. The documentary focused on parents who claimed that their children were suffering from the harmful effects of diphtheria, pertussis, and tetanus (DPT) vaccine. Physicians who agreed that the DPT vaccine was unsafe were also interviewed. After the documentary aired, public anxiety about the effects of vaccines increased. One of those who viewed the documentary was Barbara Loe Fisher who also believed that her son had been harmed by the DPT vaccine. The program inspired her to form a group, along with other parents, called "Dissatisfied Parents Together (DPT)" which later became the National Vaccine Information Center (NVIC), a well-known anti-vaccine organization in the United States (Offit, 2011). Fisher became an unofficial spokesperson for parents concerned about the effects of vaccines and wrote a book entitled "A Shot in the Dark: Why the P in the DPT Vaccination May Be Hazardous to Your Child's Health." (Offit, 2011).

In 1998, Andrew Wakefield and his colleagues at the Royal Free Hospital School of Medicine in London published a study suggesting that the measles, mumps, and rubella (MMR) vaccine causes autism. The paper heightened public anxiety and opposition to vaccines especially for MMR, leading to an increase in the incidence rate of measles throughout England. Following the publication of Wakefield's paper, various studies were conducted to look for links between the MMR vaccine and autism, but no relationship was established (Dales et al., 2001; Farrington et al., 2001; Kaye et al., 2001; Madsen et al., 2002; Peltola et al., 1998; Taylor et al., 2002). Wakefield's findings were later found to be fraudulent, and, in 2010, the Lancet formally retracted his paper (Boom & Cunningham, 2014). In 2007, an actor, Jenny McCarthy, claimed that vaccines had caused her son's autism and publicized her beliefs on the Oprah Winfrey Show, a major television program. The following year, she led a high-profile rally against vaccines. Also in 2007, Dr. Bob Sears published a book entitled "The Vaccine Book: Making the Right Decision for Your Child," in the Sears Parenting Library. In The Vaccine Book, he validates concerns of vaccine opponents and proposes an alternative vaccination schedule (Boom & Cunningham, 2014). Offit and Moser (2009) argue that the book contains misinformation that could lead parents to hesitate about whether to vaccinate their children. Misinformation and conspiracy theories are also spread online, including through social media, which may share extensive anti-vaccine content (Mills et al., 2020; Oehler, 2019; Tasnim et al., 2020) and influence views about vaccines (Witteman & Zikmund-Fisher, 2012). A systematic review by Wang and colleagues (2019) reported misinformation related to vaccination is a much studied topic, and people often seek vaccine-related information via online or through a circle of friends (Vrdelja et al., 2018). Individuals who are part of such groups in which misinformation is circulating can amplify vaccine concerns both online and offline.

During most of the 20th century, public support for vaccination was relatively strong and the number of outbreaks and deaths due to vaccine-preventable diseases declined (Dubé, Vivion, et al., 2015; Poland & Jacobson, 2011). However, towards the end of the century, the anti-vaccine movement began to grow as parents became increasingly concerned about the safety and side effects of vaccines (Burki, 2020; Dubé, Vivion, et al., 2015; Poland & Jacobson, 2011; Robertson et al., 2021). Individuals who delay or refuse vaccinations because of their beliefs increase the likelihood of infections spreading, a topic which will be discussed further in the next section.

1.2.4 Vaccine hesitancy and refusal

The term "hesitancy" implies a state of indecision or reluctance (Larson, 2013). People who are hesitant about vaccines may postpone or refuse vaccination. They may also accept the use of vaccines even though they have doubts. Vaccine hesitancy may influence both vaccine coverage and distribution patterns of infection among populations. As discussed previously in sections 1.1.5 and 1.1.6, both of these are important determinants of community immunity.

According to the World Health Organization's Strategic Advisory Group of Experts (WHO SAGE), vaccine hesitancy refers to delay in acceptance of vaccines or refusal of vaccination despite availability of vaccination services. Vaccine hesitancy is complex, and context specific, varying across time, place, and vaccines. MacDonald and colleagues explain that it is influenced by factors such as, "complacency (perceived risks of vaccine-preventable diseases are low and vaccination is not deemed a necessary preventive action), convenience (physical availability, affordability and willingness-to-pay, geographical accessibility, ability to understand (language and health literacy) and appeal of immunization services affect uptake), and confidence (trust in (i) the effectiveness and safety of vaccines; (ii) the system that delivers them,including the reliability and competence of the health services and health professionals and (iii) the motivations of policy-makers who decide on the needed vaccines.)" (MacDonald, 2015).

Benin's (2006) definition of vaccine hesitancy was developed to explain how mothers decide whether to vaccinate their children. According to Benin, vaccine hesitancy is a behavioural phenomenon, which depends on various factors, namely whether the vaccines and their providers are trusted, whether the vaccine is perceived as necessary and the level of inconvenience associated with vaccination (Benin et al., 2006). In a review of vaccine hesitancy, Dubé and colleagues (2013) argued that it is difficult to categorize attitudes towards vaccination simplistically because attitudes are shaped by a variety of social, cultural, political, and individual factors, each of which influences whether or not a person decides to get vaccinated. Opel and colleagues (2011) suggest the phenomenon is linked to beliefs about the safety and efficacy of vaccines as well as to attitudes regarding their acceptability. MacDonald (2015) argues that vaccine hesitancy lies on a continuum between high demand for vaccines and no demand (Figure 1). This conceptualization allows vaccine-hesitant individuals to hold a variety of related viewpoints, which determine whether they accept, delay or refuse vaccination. A 2016 study by the Canadian Immunization Research Network (CIRN) led by Dr. Ève Dubé concluded that, in Canada, vaccine hesitancy should not be defined only as a binary behavioural outcome (vaccine acceptance or refusal). Rather, vaccine hesitancy may be reflected in attitudes or beliefs about vaccines (e.g., concerns about their safety) independently of behavioural choices (e.g., delays, the number of vaccines refused) (Dubé et al., 2016). The varied definitions of the term vaccine hesitancy establish a need for a clear definition to design interventions and improve vaccine acceptance (Bedford et al., 2018).

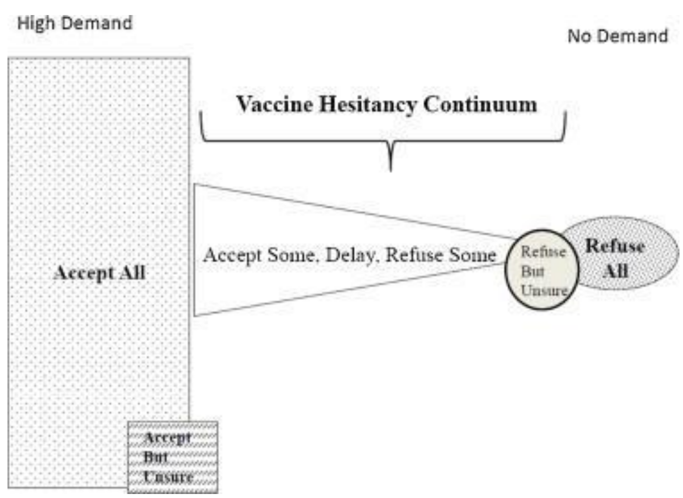

Figure 1: Vaccine hesitancy continuum (Source: MacDonald (2015, pp.4162))

Social networks and groups may determine whether a person accepts, refuses or delays vaccination (Eames, 2009). Strategic Advisory Group of Experts has recognized that vaccine hesitancy is influenced by individual or collective perceptions, beliefs, and behavioural choices, as well as contextual factors such as the media and communication environment, geographical barriers, religious beliefs, culture, and socio-economic considerations (MacDonald, 2015). Interventions that take these factors into account may be able to address vaccine hesitancy more effectively (MacDonald, 2015).

Outbreaks of vaccine-preventable diseases often occur in communities that are clustered geographically or that share a set of philosophical or cultural beliefs (Omer et al., 2009). In these communities, members who avoid vaccination are often indirectly protected by those who are vaccinated (community immunity) (De Jong & Bouma, 2001). However, shared belief systems can lead to clusters of unvaccinated individuals (Salathé & Bonhoeffer, 2008).Taking social clustering into account is therefore important for identifying which groups are at greater risk for infection and require vaccination. Social clustering or grouping can take various forms. Some examples include group formation among parents who decide not to vaccinate their children, clustering among religious people who believe vaccination goes against their beliefs, and geographical clustering. Immunization rates in these types of social groupings are usually low and can even fall below the herd immunity threshold. Group members may only mix with other members of the same community, which can increase the risk of infection and disease outbreaks (Eames, 2009; Feikin et al., 2000; Lieu et al., 2015; van den Hof et al., 2001). For instance, a recent study established a link between vaccine hesitancy and the spread of measles and pertussis among unvaccinated groups (Phadke et al., 2016). The 2017 measles outbreak in Minnesota suggested that the geographic proximity of communities with low vaccine coverage may have put people at higher risk of being infected (Leslie et al., 2018). Same trends are observed during 2020 COVID-19 pandemic, where states with lower vaccine uptake are having higher case counts (Siegel et al., 2021).

Vaccine hesitancy has played a major role in the spread of vaccine-preventable diseases by pushing the rate of vaccine coverage below the threshold required for community immunity. Maintaining the required threshold is challenging when individuals are unwilling to vaccinate themselves or their children in order to provide indirect protection to others (Calandrillo, 2003). Unwillingness combined with waning immunity among teenagers and young adults, who may or may not have received booster vaccines, may contribute to outbreaks (Lewnard & Grad, 2018). Developed countries such as the United States, Canada, and parts of Western Europe—where access to vaccines is not a major issue—have seen major outbreaks of infections among children aged 15 and older (Cortés et al., 2012; De Serres et al., 2012; Fefferman & Naumova, 2015). A study on measles outbreaks in France revealed that the percentage of young adults aged 20 affected by the disease had jumped from 17% in 2008 to 38% in 2010 and that older people who contracted the infection had developed complications (du Châtelet et al., 2010). Similarly, in Italy, a rubella outbreak in 2008 primarily affected young adults between the ages of 20 and 29, including pregnant women who subsequently underwent abortions (D'Agaro et al., 2010). An outbreak of measles in 2014 at Disneyland in California highlighted the problem of waning immunity associated with the vaccine refusal (Majumder et al., 2015). Those infected during the outbreak represented two-thirds of the total measles cases reported in April 2015 in the United States, Canada, and in Mexico (Clemmons et al., 2015). Almost half of the reported cases consisted of individuals who were not vaccinated either because they were ineligible (e.g. immunocompromised patients) or because they had refused vaccination, whether for philosophical and religious reasons or because of doubts and concerns (Clemmons et al., 2015). Social clusters formed by individuals who reject vaccines for religious reasons can also lead to outbreaks, as was the case in the United States where Amish communities were affected by outbreaks of pertussis, measles, and rubella (May & Silverman, 2003). A study in Ecuador demonstrated that despite high vaccination coverage overall, measles outbreaks occurred more frequently among subpopulations that had lower vaccination coverage compared to their neighbouring subpopulations (Rivadeneira et al., 2018).

The COVID-19 pandemic is a massive global health crisis. It has affected millions of people worldwide. Hygiene, behavioural measures, government-driven restrictions, and a global rolling out of the vaccination programme showed promise in mitigating the levels of illness, mortality, and decreasing hospital admissions (Schaffer DeRoo et al., 2020). However, a successful worldwide vaccination campaign will require not only sufficient supply and distribution but also high uptake of vaccines. Low vaccine confidence, concerns about vaccine safety and efficacy, and perceiving information to be inconsistent and contradictory are some of the challenges underlying hesitancy towards COVID-19 vaccines (Soares et al., 2021).

Even before the COVID-19 pandemic, vaccine hesitancy had become a recognized global threat (Hancock, 2019; *Ten Health Issues WHO Will Tackle This Year*, 2019). Despite being well documented as one of the most successful public health measures, vaccination is perceived by some groups as unsafe and a non-essential procedure (Dubé et al., 2013). The challenges in ensuring that individuals and communities accept vaccines are multifaceted. Reasons for vaccine hesitancy include concerns about vaccine safety (as seen with COVID-19 vaccines (Fridman et al., 2021; Karlsson et al., 2021)), mistrust of healthcare professionals, geographical barriers, religious beliefs, and ethical objections (Omer et al., 2009) and inaccurate mental models (Downs et al., 2008). Poor communication about the merits of vaccines and how they work may also contribute to the vaccine refusal (Leask et al., 2012). In other words, for some people, accepting vaccines can be a complicated process involving cognitive, emotional, cultural, social, spiritual, and political considerations (Dubé et al., 2013; Hobson-West, 2003; Streefland et al., 1999). Addressing vaccine hesitancy is important and requires understanding factors that influence it in order to develop strategies to address those factors. Interventions to secure high levels of childhood vaccination require at least 95% of coverage e.g., for measles recommended by the WHO (to sustain community immunity) is a public health priority (World Health Organization, 2019). The next section discusses interventions designed to address vaccine hesitancy.

1.2.5 Interventions to address vaccine hesitancy

Considerable efforts have been made to encourage vaccine uptake and to prevent the outbreak of diseases (Dubé, Gagnon, et al., 2015; Jarrett et al., 2015). This section will briefly describe the different interventions that address vaccine hesitancy, which can be broadly grouped into five categories:

- Incentive-based interventions
- Reminder or recall-based interventions
- Educational: individual interventions
- Educational: community interventions
- Patient decision aids

Incentive-based interventions are strategies that encourage vaccination by providing incentives such as money, food, or other goods to people who vaccinate themselves or their family. This method has been shown to increase vaccination uptake among underserved groups that struggle with basic community needs (Jarrett et al., 2015; Machado et al., 2021). For instance, a study conducted in India showed that immunization rates improved when people were given lentils or metal plates after getting vaccinated (Banerjee et al., 2010).

Reminder or recall interventions take the form of telephone calls, letters, and text messages. This strategy may increase vaccination when people are willing to be vaccinated but may not remember the complex immunization schedules (e.g., multiple or booster doses) (Jarrett et al., 2015; Machado et al., 2021). A study in Pakistan showed this method was effective in reducing the number of children who did not complete immunization programs (Usman et al., 2009). Poorman and colleagues (2015) by referring in their review to a cohort study which showed that parents who received text message reminders were more likely to complete the series of HPV vaccination for their children.

Educational interventions seek to help people and communities to understand the benefits and importance of immunization (Willis et al., 2013). A review by Jarrett and colleagues (2015) suggested that education campaigns are more effective in changing people's understanding and attitudes towards vaccines than incentive-based and recall interventions. A review by Machado and colleagues (2021) suggested that multi component strategies grouped with education about immunization may improve immunization uptake. Education strategies can target individuals or communities.

Educational individual interventions inform individuals about vaccines through, for instance, brochures, leaflets, talk sessions, lectures, group seminars and home visits (Kaufman et al., 2013). Cairns and colleagues (2012) examined various communication strategies that have been used to promote vaccine uptake and found that dialogue and face-to-face communication may improve people's knowledge and attitudes regarding vaccination. However, another review by Kaufman and colleagues (2013) reported uncertain effects of face-to-face interventions and also reported that studies evaluating them provide low quality evidence. The independent effectiveness of each of these different strategies is difficult to evaluate as many interventions combine multiple strategies; for example, information given through pamphlets or brochures along with face-to-face education for individuals (Dubé, Gagnon, et al., 2015; Kaufman et al., 2013).

Motivational interviewing is a particular form of educational individual intervention to address vaccine hesitancy and increase vaccine acceptance (Cole et al., 2021; Gagneur, Bergeron, et al., 2019; Gagneur, Gosselin, et al., 2019). Motivational interviewing is a person-centered tool which supports decision making by enhancing internal motivation to change behaviour based on a person's own arguments for change (Rollnick et al., 2008). With regard to immunization, the motivational interviewing approach aims to inform people (parents or caregivers) about vaccinations by addressing individual specific needs and level of knowledge while respecting their beliefs (Gagneur, 2020). Within a study arm of a randomized controlled trial in Quebec, Gagneur and colleagues (2019) showed that parents of newborns who received a motivational interviewing intervention demonstrated an overall 12 percentage point increase in vaccination intention (pre-motivational interviewing 78% vs post-motivational interviewing 90%, $p < 0.0001$), and an 11 percentage point decrease in vaccine hesitancy (27% pre-motivational interviewing vs 16% post-motivational interviewing, $p < 0.0001$.)

Educational community interventions are directed towards groups of people who share a similar geography as well as similar cultural and or social characteristics (Baker et al., 2011; Saeterdal et al., 2014). Information can be delivered through community meetings, posters, flyers, billboards, newspapers, television and radio (Saeterdal et al., 2014). Outreach sessions, such as door-to-door visits by health workers or involving religious or traditional leaders in dialogue exchange can also be helpful in addressing misconceptions, rumours and distrust within communities regarding vaccination (Obregón et al., 2009). Studies conducted in Pakistan, India and Nigeria found that the involvement of religious and community leaders in health promotion campaigns encourages community acceptance of vaccines and leads to higher rates of vaccine uptake (Lahariya et al., 2007; Nasiru et al., 2013; Obregón et al., 2009). Saeterdal and colleagues (2014) conducted a review of community-level interventions. This review examined two studies, one from Pakistan and another from India, in which people in small communities were given information about vaccines, vaccination rates and the cost and benefits of childhood vaccination (Andersson et al., 2009; Pandey et al., 2007). While the interventions did increase community willingness to participate in vaccination programs, it is uncertain whether they improved people's knowledge and attitudes towards vaccines (Saeterdal et al., 2014). Further, it must be noted that sometimes low vaccination coverage may stem from issues such as vaccine shortages or unsafe working conditions for health care workers (Abimbola et al., 2013; Closser & Jooma, 2013; Subhani et al., 2015). In such cases, educational community interventions would not address the problem.

In addition to leaflets, brochures, media outlets and personal outreach, educational interventions—both individual and community—can also use digital media. This form of media delivers health information through mobile phones via text messages and smartphone applications or by using internet-based tools such as email, social networking platforms, and web portals. A systematic review by Odone and colleagues (2015) reported that internet-based educational interventions may encourage vaccine uptake. A randomized controlled trial showed improved parental attitudes towards vaccines with internet-based interventions (Daley et al., 2018). A randomized controlled trial by Lau and colleagues (2012) assessed the impact of personalized web-based health management systems on influenza vaccine uptake and utilization of healthcare services among university students and staff. They noted that personalizing web portals – displaying a patient's preferred language, including the patient's name, allowing the user to interact with providers – increased influenza vaccination uptake from 4.9% to 11.6% (Chi-squared=7.1, p=0.008). Digital media is adaptable and allows personalization and dissemination of messages at relatively low cost (Cooney et al., 2010; Cushing & Steele, 2010; Webb et al., 2010) A systematic review conducted by Ohannessian and colleagues reviewed vaccination-related serious video games. They reported 92% who played these games agreed to get vaccinated thus making serious video games a potentially useful tool for educating people to get immunized (Ohannessian et al., 2016). However, very few interventions using digital media have been evaluated and they may not reach people with limited computer skills or who lack internet access (Dubé, Gagnon, et al., 2015).

Patient decision aids are tools that support health-related decision making by providing, at a minimum, information on the options and outcomes relevant to a person's health status and implicit or explicit support to help them clarify what matters to them relevant to the decision (Stacey et al., 2017). In other words, like motivational interviewing, patient decision aids go beyond educational interventions by explicitly supporting the process of making a health-related decision. As such, they can complement counselling from health care professionals, allowing patients to make decisions that are evidence-based, informed and in line with their own values (Barry & Edgman-Levitan, 2012; Makoul & Clayman, 2006; Mulley et al., 2012). Two systematic reviews and meta-analyses showed that patient decision aids reduce decision conflicts and may promote vaccine acceptance (Bruel et al., 2020;

Vujovich-Dunn et al., 2021). A systematic review by Bruel and colleagues (2020) evaluated decision aids in the vaccination context (n=8), they reported that out of 8 included studies two showed an improvement in vaccine coverage, two studies showed an improvement in vaccination intention, without objective assessment of vaccine coverage, and the studies that have assessed decision conflict all found a decrease in it through decision aids. A systematic review and meta-analysis of five randomized controlled trials (total n=2158) of decision aids for immunization decisions by Vujovich-Dunn and colleagues (2021) showed, the overall effect estimate of decision aids was 1.89 (95% CI: 1.20–2.97) on vaccine intentions and 1.77 (95% CI: 1.25–2.52) on vaccine uptake.

1.2.6 The role of emotions in decision making

Terminology: Affect, Feelings, Emotions

The terms a*ffect*, *feelings*, and *emotions* can be difficult to differentiate, which may lead to inconsistency in understanding and using these terms. Affect is a broad term used in psychology to describe feelings, emotions, and other emotion-related attributes (Fleckenstein, 1991; Lerner et al., 2015). Thoits (1989) defined affect as the positive and negative evaluation of an object, behaviour, or an idea. The conscious expressions of affect are feelings and emotions (Munezero et al., 2014). In addition, feelings can be defined as experiences of physical or psychological states such as hunger, pain, and fatigue, which correspond to subjective feelings of emotion (Fleckenstein, 1991; Friedenberg & Silverman, 2011; Thoits, 1989). Emotions are projections or displays of culturally or socially determined feelings or affect (Shouse, 2005; Thoits, 1989). Emotions are considered to be expressions of affect. When people interact with their environment, they experience a positive or negative affective reaction, which translates into an emotional response (Munezero et al., 2014). Scherer (2005) defined emotion as an affective experience such as anger, fear, joy, or disgust. There are eight primary emotions that have been identified as influencing people’s choices and behaviour: joy, sadness, trust, disgust, fear, anger, surprise, and anticipation (Plutchik & Kellerman, 1980).

Affect and emotions are often used interchangeably in the scientific literature. In this work, I refer to affect when describing people’s underlying reactions, and emotions when referring to their conscious or unconscious expressions of affect.

The four functions of affect

Peters and colleagues (2006) proposed that affect has four major functions in judgment and decision making. These are: affect as information, as a spotlight, as a motivator, and as common currency (Ellen Peters et al., 2006).

Affect as information suggests that affect develops through experience, providing information about what to choose and what to avoid (Damasio, 1994). For example, Peters, Solvic and Hibbard (2004) found that people determine the costs and benefits of unfamiliar health plans by using affective cues to interpret numerical information. Therefore, health-related judgments and preferences, such as a new medical treatment, can be based not only on what people think about the treatment but also on how they feel about it. In other words, if a person's feelings toward a vaccine are favorable, then the vaccine's benefits will be perceived as greater than the risks, and vice versa.

Affect functions *as a spotlight* by using feelings to direct a person's cognitive perceptions. Specifically, affective feelings guide decision-makers focus on certain information which in turn shapes their judgments and decisions (Ellen Peters et al., 2006). The type of information to which people look depends on how they feel about the topic or issue. For example, if a decision maker feels positively about radiation sources (e.g., X-rays) then the benefits of radiation will be focused on more than the risks. However, the reverse could happen if a patient's feelings about radiation sources are negative due, for instance, to its association with nuclear power (Alhakami & Slovic, 1994). Research has shown that viewing an anti-vaccine website for a few minutes can influence individual risk perception (Betsch et al., 2010) which may influence decisions regarding vaccine uptake. This may occur because anti-vaccine information may act as a spotlight, provoking negative feelings towards vaccines and influencing risk perception and vaccine decisions.

The third function of *affect is to motivate action* (Ellen Peters et al., 2006). Affect tends to classify stimuli into good or bad, which may link to behavioural changes (Leventhal, 1970; Sutton, 1982; Witte, 1998). People naturally pursue actions that elicit good feelings and avoid those that cause negative sensations (M. Chen & Bargh, 1999). This function of affect may help motivate preventive behaviours (Turner & Underhill, 2012). For example, caregivers intend to get vaccines for COVID-19 vaccines to protect their child (Goldman et al., 2020). This suggests that when people feel that vaccines help them and their loved ones from being infected and spreading contagious diseases, they tend to take preventive action.

Lastly, affect serves as a *common currency*, allowing people to compare the merits of various options that are otherwise misunderstood (Ellen Peters et al., 2006). For example, affect provides an avenue for people to weigh quality of life against length of life—two concepts that are otherwise difficult to compare. As such, people are able to incorporate cost-benefit analyses into their decision making (Trafimow & Sheeran, 2004). In the case of vaccines, when making vaccination decisions, people may use their feelings to weigh incommensurate risks and benefits; for example, the risk of needing to take a day or two off work and the benefit of avoiding transmitting an infectious disease to others.

The role of emotions in decision making

People process information and make decisions by using their emotions to appraise situations (Lerner & Tiedens, 2006; So et al., 2015). Smith and Ellsworth (1985) suggested that appraisal consists of eight dimensions. These include: pleasantness, certainty, attention, responsibility, perceived obstacle, legitimacy, anticipated effort, and situational control. Every emotion can be defined with respect to each of these elements. Lerner and Tiedens (2006) later proposed that certain emotions, such as anger and fear, can be associated with different appraisal dimensions, depending on the context in which the emotion is experienced. As a result, even though anger is generally associated with negative emotions, it can have a positive impact if it motivates people (Lerner & Tiedens, 2006).

According to Epstein (1994), humans make choices using dual modes of information processing, namely, experiential and rational processing. Experiential processing is intuitive, quick, and relies on “gut feelings” or emotions, while deliberative or rational processing is slow, requires effort, and involves explicit reasoning, such as making lists of pros and cons (Evans & Stanovich, 2013). Many psychologists argue that emotions are the dominant driver for most meaningful decisions in life (Frijda, 1986; Keltner et al., 2013; Keltner & Lerner, 2010; G. F. Loewenstein et al., 2001). Emotions also guide everyday decision making by reducing negative feelings like guilt and regret and increasing positive feelings such as pride and happiness, even when people are unaware of it (Keltner & Lerner, 2010; G. Loewenstein & Lerner, 2003).

Studies conducted with patients who have neurological injuries to the ventromedial prefrontal cortex, a key area of the brain for integrating emotion and cognition, show that such neurological impairments reduce both the ability to feel emotions and make optimal decisions (Bechara et al., 1999; Damasio, 1994). When these study participants were asked to choose financial options, they repeatedly selected riskier financial options over safer ones despite being aware of the risks. Bechara & Damasio (2005) and Bechara and colleagues (1999) explained that people behaved this way because of their inability to experience emotional signals, such as somatic markers, that lead normal decision-makers to be risk averse.

Health situations may elicit emotions that complicate decision making. For instance, when patients receive health-related information, they might feel certain emotions such as fear, anxiety, joy, happiness, and distress (Reyna, 2004; Rothman & Kiviniemi, 1999). Patients may rely more on their emotions when there is pressure to make a decision (Revenson & Pranikoff, 2005). In the case of vaccination, people may rely on emotional, cultural, and social factors before making a decision (Dubé et al., 2013; Hobson-West, 2003; Streefland et al., 1999). As a result, individuals might reject immunization because of unpleasant emotions towards vaccination, such as fears over vaccine safety (Gavaruzzi et al., 2021; Tomljenovic et al., 2020). They may also decide to get vaccinated because feeling safe from a disease elicits positive emotions (Bendau et al., 2021).

Emotions also influence decisions by influencing behavioural intentions and attitudes. Pratkanis (1989) proposed that attitudes serve as heuristics, with positive attitudes allowing a favourable response, while negative attitudes will permit unwillingness towards certain activities. Studies have shown associations between affect and attitudes (Fazio, 1995; Kahneman et al., 1998; Kahneman & Ritov, 1994). For instance, Kahneman and colleagues have shown in their studies that willingness to pay for public goods or paying damages for personal injuries are associated with attitude, based on emotions (Kahneman et al., 1998; Kahneman & Ritov, 1994). Therefore, risk perception is not merely cognitive but also emotional. Loewenstein referred to this framing of risk perception as the 'risk as feelings' hypothesis (G. F. Loewenstein et al., 2001). When information about specific risk is provided, people often tend to translate it intuitively, which may represent itself in the form of anxiety, worry or distress (Reyna, 2004). Such emotions therefore may have an impact on people's responses to their health conditions (Ellis et al., 2018; McCaul & Tulloch, 1998; Rothman & Kiviniemi, 1999; Trask et al., 2001). Zikmund-Fisher et al., (2010) provide a review of research that revealed the ways emotions can influence people's cancer-related decisions. Their results showed that people extract meaning from the numerical information of risk from such communication as, "how high or low is the risk," or, "is there something to worry about or to be relieved about," (Zikmund-Fisher et al., 2010). Thus, emotional reactions such as concern, relief, or surprise to risk information may influence people's choice of care.

1.3 Visualization

1.3.1 Definition and motivation

Visualization refers to a visual presentation of data or information, which may be static, dynamic, or interactive. Visualization is a powerful mechanism for communication because it enables people to rapidly understand complex information such as patterns within a large dataset (Michalos, Tselenti, & Nalmpantis, 2012).

1.3.2 How visualization works

Communicating information through visualization may be an effective tool because of human vision pre-attentive processing (H. M. Chen, 2017). Among humans who can see, pre-attentive processing allows people to notice and process visual information very quickly (Costa et al., 2020). One important feature of human vision is to rapidly and automatically categorize images into regions and properties, based on simultaneous computations across an image (C. Healey & Enns, 2012). Visual features that are detected pre-attentively include: orientation, length, closure, size, curvature, density, intensity, number, hue (colour), luminance, intersections, terminators, 3D depth, flicker, direction of motion, velocity of motion, and lighting direction (C. Healey & Enns, 2012). By pre-attentively detecting individual visual features or combinations of visual features, people are therefore able to perform pre-attentive visual tasks such as: target detection, boundary detection, region tracking, and counting and estimation (Marmo & Valle, 2005).

Target detection is a visual property which allows a viewer to tell at a glance whether the target is present or absent. This feature is used to rapidly identify the presence or absence of the target; e.g. pre-attentively identifying the empty circle (target) among filled circles (Figure 2).

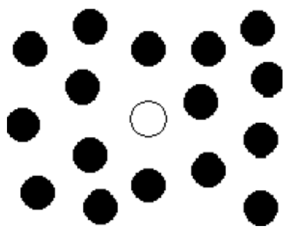

Figure 2: Target detection (Source: Marmo & Valle (2005, pp.113))

In *boundary detection*, a viewer attempts to detect rapidly and accurately a texture boundary between two groups of elements, where all elements in each group have a common visual property (Figure 3).

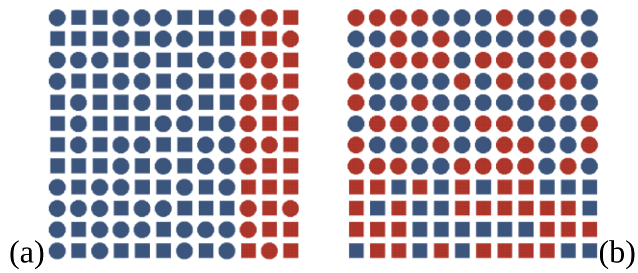

Figure 3: Region segregation by form and hue: (a) hue boundary is identified pre-attentively, even though form varies in the two regions; (b) random hue variations interfere with the identification of a region boundary based on form. (Source: Healey (2001, pp.124))

Region tracking allows a viewer to track one or more elements with a unique visual feature as they move dynamically in time and space.

Counting and estimating allow a viewer to count or estimate the number of elements in a display that share a unique visual feature (Figure 4).

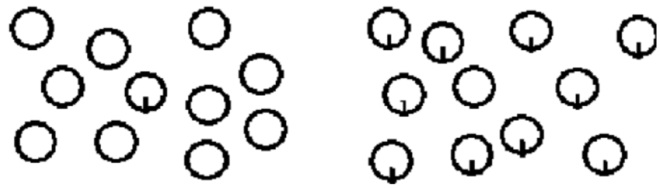

Figure 4: Counting and estimating (Source: Marmo & Valle, (2005, pp.114))

These pre-attentive visual properties play a critical role in early visual processes (Costa et al., 2020) and features like hue (colour) is not an only feature which is detected pre-attentively but, users can identify targets with the help of other features such as difference in curvature (C. Healey & Enns, 2012). Proper choice of visual features will draw attention to areas of a visualization that contain important information. This encourages understanding by influencing human visual processes to facilitate the detection of patterns, such as trends and outliers in a given graphical or statistical visualization (C. Healey & Enns, 2012; Heer et al., 2010).

1.3.3 Visualization techniques

Visualization aims to represent information clearly. Frequently-used forms of visualization are bar charts, pie charts, line graphs, geographic maps, icon arrays, and visual scales. Newer visualization forms and techniques have also been enabled by advancements in computer technologies (Nelson et al., 2009).

Many different visualization techniques exist. Below, I present examples of some currently-used techniques: time series data techniques, statistical distributions, hierarchies, and networks.

Time series data techniques

Time series data techniques display values over time (Michalos et al., 2012). Time series data techniques are mostly used to display data in domains such as finance displaying stock prices and exchange rates, science showing temperatures, pollution levels, and public policy to present data such as crime rates (Heer et al., 2010). Time series data techniques should help the viewer efficiently distinguish, analyse and compare multiple time series datasets. Some examples of time series data techniques are: index charts, stacked graphs, small multiples, and horizon graphs.

Statistical distributions

Statistical distributions are presented visually to reveal how a set of numbers is distributed and help the viewer understand the statistical properties of the data. It is mostly used in data analysis for gaining insight for how data is distributed to inform data transformation and modeling decisions (Heer et al., 2010). Common techniques include histograms, stem and leaf plots, QQ plots (quantile-quantile plots), SPLOM (scatter plot matrices), and parallel coordinates.

Hierarchies

Hierarchies display data with a hierarchical system structure. Some common hierarchical system techniques include node link diagrams, adjacency diagrams, and enclosure diagrams. For instance, Figure 5 presents a node link diagram showing the structure of burden placed on people living with chronic illness.

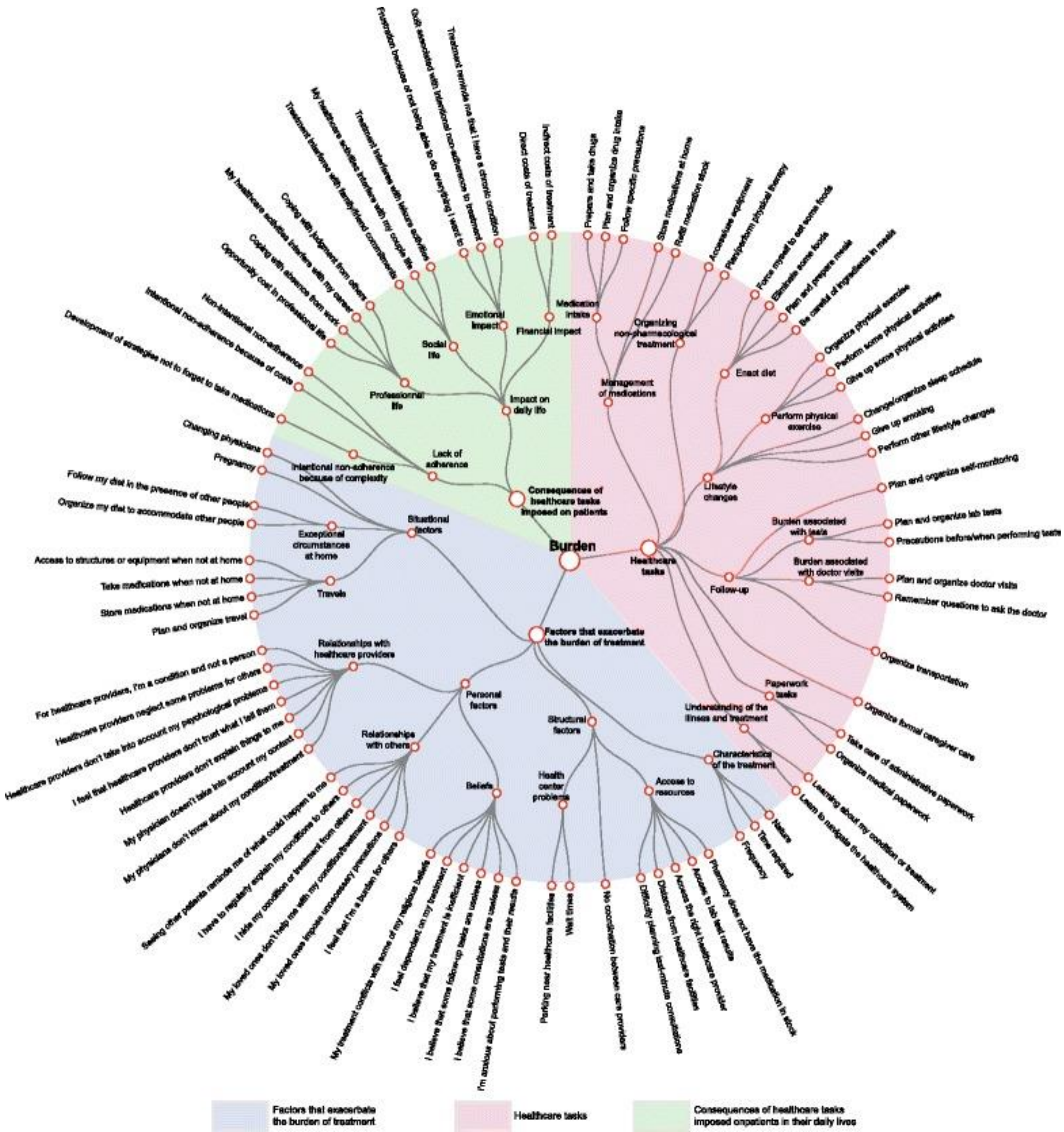

Figure 5: Hierarchies (Source: Tran et al., (2015, pp.6))

Networks

A network refers to an object composed of elements and relationships or connections between those elements.The networks visualization techniques enable the representation of categories and connections including social networks, epidemiological concepts, bioinformatics topics, and complex systems (Heer & Shneiderman, 2012). Examples of this technique include force-directed layouts, arc diagrams, and matrix views (Nagel & Duval, 2013).

1.3.4 Visualization in health communication

Visualization is a technique for communicating data and information, including about risk. Risk communication is a broad term which refers to interactive exchanges of information about the type and magnitude of an outcome that can be expected due to an exposure or a behaviour (Berry, 2004; Glik, 2007; Goldstein, 2005; Morgan, 2002; Reynolds & W. Seeger, 2005). One of the key challenges addressed by visualization is helping people understand numerical expressions of risk such as probabilities, fractions, and ratios in the context of health communication and decision making (Fagerlin, Ubel, et al., 2007; Galesic & Garcia-Retamero, 2010; Lipkus et al., 2001). People make health-related decisions based at least partly on their understanding of the numerical information presented (Fagerlin et al., 2005; López-Pérez et al., 2015; Zikmund-Fisher et al., 2017).

The purpose of communicating health data and information is to facilitate informed decision making (Nelson et al., 2009). Health decision making therefore requires that information about risk be adequately represented through words, numbers, and symbols. Risk can be communicated through visualization in a number of ways, ranging from numerical displays to more complex options such as maps, icons, and visual symbols. However, inadequate formats can mislead people (Gigerenzer et al., 2007) and representing numerical information adequately remains an ongoing challenge (Garcia-Retamero & Galesic, 2010). To address this challenge, many studies have evaluated visualizations designed to convey quantitative health information, finding that such visualizations (example, see Figure 6) can increase people's understanding of health-related risks (Fagerlin, Zikmund-Fisher, et al., 2007; Garcia-Retamero & Galesic, 2010; Hawley et al., 2008; Paling, 2003; Ellen Peters, 2012). A review by Garcia-Retamero & Cokely (2013) noted that visualizations improve the capacity of patients to make informed health decisions. Visualizations help people with lower literacy and numeracy skills and low native language proficiency to better understand medical information (Garcia-Retamero & Dhami, 2011; Garcia-Retamero & Galesic, 2010). Visualizations such as icon arrays can also improve people's understanding of risk (Hawley et al., 2008) and reduce biases (Okan et al., 2015). Furthermore, it has been demonstrated that visual analogy can improve comprehension (Reading Turchioe et al., 2020) and visualizations can assist people at higher risk in making decisions and possibly modify their attitude towards medical screening procedures (Garcia-Retamero & Cokely, 2011). A systematic review reported that communicating risk through visual aids helps people better understand risk and can elicit positive changes in behavioural intentions, attitudes, and trust (Garcia-Retamero & Cokely, 2017).

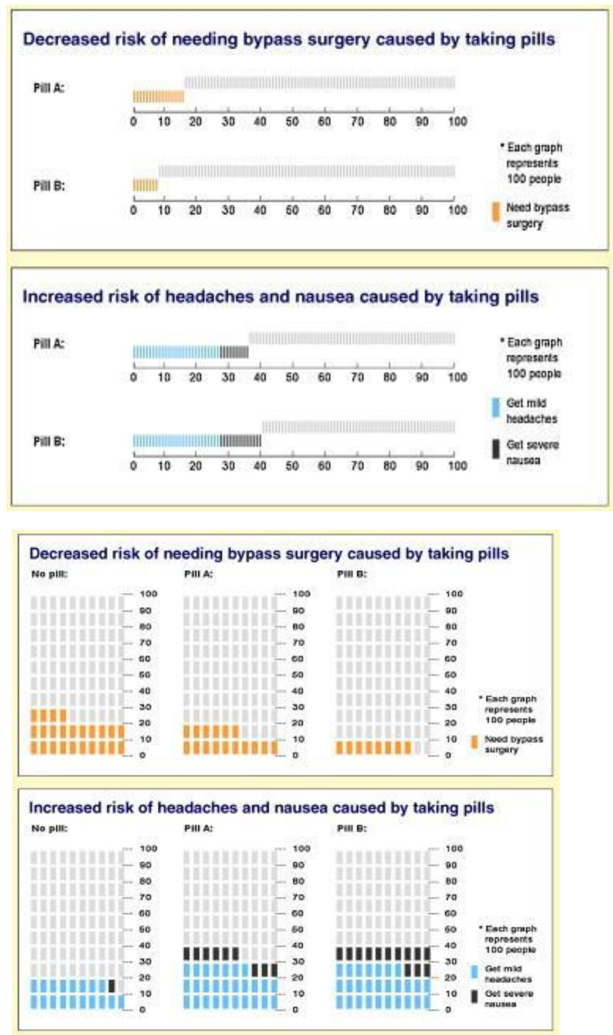

Figure 6: Sparkplugs (left) and Icon Arrays/Pictographs (right)
(Source: Hawley et al.(2008, pp.4))

1.3.5 Visualization and immunization

Health decision making presents additional complexity when it affects the safety of others (Jonas et al., 2005a), as is the case with vaccination. Visualizations can give people the tools needed to better understand the risks and benefits involved and to make an informed decision about vaccination. A randomized controlled trial by Shourie and colleagues (2013) indicated that visual, web-based patient decision aids reduced parents' decisional conflict regarding measles, mumps, and rubella vaccination. People are more likely to indicate an intention to vaccinate their child against influenza when benefits and risks are communicated according to best practices and when people are provided with a dynamic visualization showing how what matters to them aligns or fails to align with the options of vaccinating versus not vaccinating (Witteman, Dansokho, Exe, et al., 2015). It has been suggested that visually-enhanced tools could improve rates of immunization (Papachrisanthou et al., 2016). Concepts like how vaccines work, vaccine safety, and herd immunity when explained with creative videos have a more positive impact on general public trust than simple infographics (Alstyne et al., 2018).

However, few visualizations are available that convey the concept of community immunity. For example, The Guardian, a newspaper based in the United Kingdom, created an interactive visualization showing the role of community immunity in measles (Harris et al., 2015), but has not evaluated the effects of the visualization on readers. Betsch and colleagues (2017) are the only team to have developed and evaluated an interactive visualization explaining how community immunity works. Their visualization increased vaccination intentions and demonstrated the promise of this medium for conveying the concept of community immunity among the general population. In addition, other studies have also pointed to the potential advantages of using visualization and videos to convey the concept of community immunity (Alstyne et al., 2018; Nowak et al., 2020).

In summary, little is known about the effectiveness of visualizations of community immunity. An emotionally-salient visualization that is designed to be understandable across all levels of education could help people understand the dynamic interplay between individual-level behaviour and community immunity. If effective, such a visualization could later be used as part of larger interventions to help people make evidence-informed decisions about vaccination.

Chapter 2: Objective and Specific Aims

The overarching objective motivating this thesis was to determine how to communicate the concept of community immunity to a wide range of the Canadian public. To achieve this objective, I developed three specific aims.

Specific Aim 1 was to synthesize what approaches for communicating the concept of community immunity already existed, including whether there was evidence of their efficacy or effectiveness. Approaches could be described in the academic literature or could exist as websites available to anyone with an internet connection.

Specific Aim 2 was to develop an online application (i.e., a website) with a visualization of community immunity and iteratively optimize people's cognitive and emotional responses to the application.

Specific Aim 3 was to evaluate the effects of the application developed in Aim 2 and other approaches identified in Aim 1 or in my ongoing collection of available visualizations on risk perception (primary outcome) and on vaccination intentions, trust in information, emotions, and knowledge (secondary outcomes) among members of the Canadian general public who have access to the internet. By risk perception, I mean perceptions of risk to an individual, to one's family, to one's community, and to vulnerable people in one's community. By the Canadian general public, I mean adults living in Canada who are able to access the internet (91% of adults in Canada (Government of Canada, Statistics Canada, 2019)).

Chapter 3: Conceptual Frameworks

This interdisciplinary thesis drew on four conceptual frameworks. I used Gestalt Principles of Visualization based on Gestalt Theory to develop a visualization of community immunity. I used the Cognitive Theory of Multimedia Learning to explain cognitive responses to visualization and the Affect Heuristic to explain emotional responses to the visualization. The Health Belief Model was used to understand potential health behaviour as a result of exposure to the visualization. Below, I provide a description of each of the four frameworks, followed by the integrated conceptual framework combining the four that guided my work.

3.1 Gestalt Principles of Visualization

To develop a visualization of community immunity against vaccine-preventable diseases, I used Gestalt Principles of Visualization. Gestalt Principles were derived from Gestalt Theory, which grew out of the field of psychology and came to influence other domains like linguistics, instructional design, human-computer interaction, and art and visual communication (Behrens, 2002; Croft & Cruse, 2004; Shneiderman, 2010; Smith-Gratto & Fisher, 1999). Gestalt Theory was developed in 1920's by three German psychologists: Max Wertheimer, Kurt Koffka, and Wolfgang Kohler. Max Wertheimer described the Gestalt Theory as, "There are wholes, the behaviour of which is not determined by that of their individual elements, but where the part-processes are themselves determined by the intrinsic nature of the whole. It is the hope of the Gestalt theory to determine the nature of such wholes."(Wertheimer, 1923). In other words, it refers to aspects of structure, configuration, or layout that, when combined, are greater than the simple sum of their individual parts. In other words, the whole has a reality of its own, independent of the parts. For example, a person perceives words and clearly understands the meaning by specific configuration of alphabets. In movies, each frame is considered separately and estimated on its compositional strength, but it is the rapid movement of those multiple frames across time that form a perception of movement and narrative continuation (Graham, 2008).

Visual experts were inspired by these principles to understand human perception and the ability to group things (Chang et al., 2002; Graham, 2008; Ripalda et al., 2020). Gestalt

Principles can be used to understand how people perceive visualizations and thus help explain the effects of spacing, timing, and configuration when presenting information (Graham, 2008). There are 114 principles, some of which are more useful for visualization than others (Boring, 1942). The Gestalt Principles I used most in this thesis were: figure/ground, proximity, closure, similarity, and continuation. These principles are reliable and may provide a good platform for interactive design for improving visual and communicative tools (Graham, 2008; Ripalda et al., 2020; Sharma et al., 2020). These are described briefly below.

Figure/Ground: This principle is based on elements' contrast with its surroundings and the way we identify objects (figure) by contrast from their backgrounds (ground). Figure/ground can be used to make images and text clearly visible and distinguishable to a user (Chang et al., 2002). For example, in interactive websites or software, when the pointer of the mouse is on any text link, it changes colour or shows changes when the link is clicked (Figure 7). Conversely, when the colour is similar to the background, then it is difficult for a person to differentiate or perceive an image or text (Graham, 2008). This principle may be useful to help draw attention to individual elements within a group.

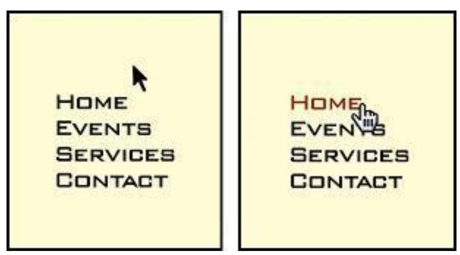

Figure 7: Figure/Ground (Source: Graham, (2008, pp.4))

Proximity: This principle stipulates that images or figures, when located near to each other, are considered as a part of the same group while objects apart are perceived as separate. This means that spacing between elements may influence perceptions of grouping (Allon et al., 2018). For example, humans are able to read and make sense of words or objects due to close proximity (Graham, 2008; Huang et al., 2021). This principle helps in visual designs by conventionally arranging the words or different objects in one group by sorting them based on their similar colour, shapes, size or any other physical attributes (Figure 8).

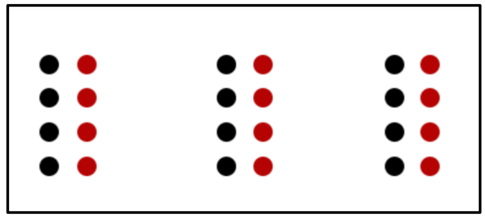

Figure 8: Proximity (Source: Bradley, (2010, pp.1))

Closure: Closure refers to the mind's tendency to automatically complete figures and forms. Humans have a natural propensity to visually close gaps into familiar forms. When any information is missing, we focus on the present parts and ignore the missing ones, filling in the missing gaps with a familiar pattern to complete the image (Figure 9) (Smith-Gratto & Fisher, 1999). The principle of closure makes a shape easier to encode (Garrigan, 2012). This principle often works in concert with another Gestalt principle known as continuation (described in the next paragraph).

Figure 9: Closure (Source: Chang et al., (2002, pp.2))

Continuation: This principle explains the relationship between shapes and has been associated with curvature (Bertamini et al., 2016). Continuation occurs when the eye moves automatically through one object, line, curve and continue to another object (Graham, 2008). For example, lines direct the human eye such that it will tend to follow animated sequences of an object, even when there is progression of change in hue, value and chroma (Figure 10) (Graham, 2008; Kepes, 1995).

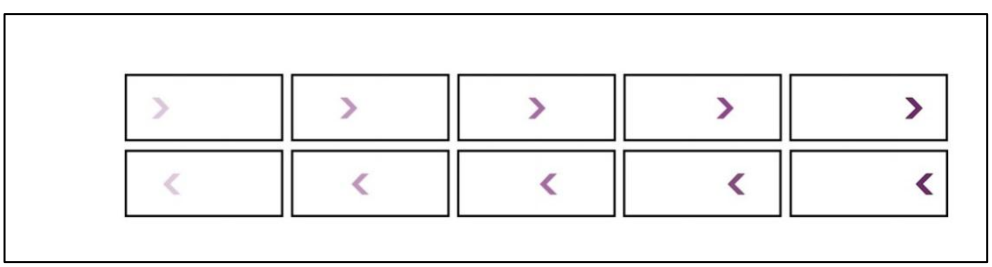

Figure 10: Continuation (Source: Graham, (2008, pp.11))

Similarity: When objects look similar in shape, size, color, direction and proximity, they are perceived as a group, physically or conceptually (Graham, 2008). For example, in

Figure 11, a person can recognise a triangle inside the square, by differentiating it from the rest of the similar shapes (Fultz, 1999).

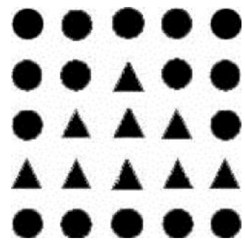

Figure 11: Similarity (Source: Chang et al., (2002, pp.3))

Gestalt principles provide a structure for understanding how human beings perceive visual presentation to achieve compelling visual results (Koffka, 2013). Gestalt principles have been applied to instructional visual designs (Benyon et al., 1994; Smith-Gratto & Fisher, 1999) and have proven to be beneficial for interactive visual screen designs and effective learning (Chang et al., 2002). These principles can be used as guiding framework in human-computer interaction to assist in creating an interface that fosters the user's engagement (Fraher & Boyd-Brent, 2010; Ripalda et al., 2020). Using Gestalt principles helped me to develop a visualization designed to help people better perceive and understand the information delivered, including identity (self, other, vulnerable), status (infected or susceptible, immunized or not), and groupings of people in a community.

3.2 Cognitive Theory of Multimedia Learning

The outcomes of interest in this study were aspects of cognition and emotion. I used the Cognitive Theory of Multimedia Learning to understand the learning process of individuals (Figure 12) (R. E. Mayer, 1997a). According to Mayer's (1997a) Cognitive Theory of Multimedia Learning, humans have two channels—auditory and visual—and use both together to build mental representations from words (audio) and pictures (R. E. Mayer, 1997a; Sorden, 2012).

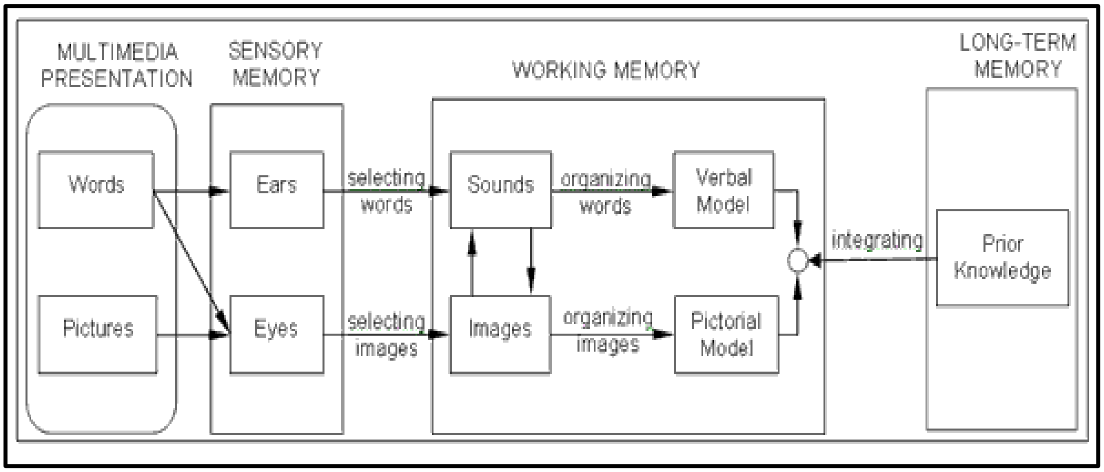

Figure 12: Cognitive theory of multimedia learning (Source: Mayer, Heiser & Lonn, (2001, pp.190))

The Cognitive Theory of Multimedia Learning postulates that to facilitate learning from multimedia, messages should be designed keeping in mind that human auditory and visual channels have limited capacity. Learning is a process of filtering and selecting from those channels simultaneously and organizing new information based on prior knowledge (R. E. Mayer, 1997a). Mayer and Moreno (2002) further suggested five instructional designs derived from the Cognitive Theory of Multimedia Learning which can minimize cognitive load and help with deep and meaningful learning. These are: Multimedia aids, Contiguity aids, Coherence aids, Modality aids, and Redundancy aids.

Multimedia may improve understanding (R. E. Mayer, 1997b; Richard E. Mayer & Moreno, 2002). Cognitive Theory of Multimedia Learning builds on three theories or classes of theories: constructivist learning theories (Cooper, 1993; Ertmer & Newby, 1993; Piaget, 2013; Vygotsky, 1980), Dual Processing Theory (Clark & Paivio, 1991; Paivio, 1990), and Cognitive Load Theory (Baddeley, 1992; Chandler & Sweller, 1991; Sweller, 1999). Constructive Learning Theory contributes the concept that for meaningful learning to occur, a learner actively selects and organizes information into a coherent representation which is integrated with their prior knowledge and does not overload the information channels (Richard E. Mayer, 1996, 1999; Wittrock, 1990). Dual Processing Theory contributes to the concept that visual and verbal processing are done in different channel systems of the human brain (Clark & Paivio, 1991; Paivio, 1990). The verbal channels take input from the ears and then represent it verbally whereas the eyes take the visual input and form a pictorial representation in the brain (Richard E. Mayer & Moreno, 2002). Cognitive Load Theory contributes the concept that the processing capacity of information channels is limited (Baddeley, 1992; Chandler & Sweller, 1991; Sweller, 1999). Therefore, too many words, complex images, and information may overload the visual and verbal processing systems (Richard E. Mayer & Moreno, 2002).

Multimedia aids assume that when narration (words) and animation (pictures) are presented at the same time, the learner can develop a deeper understanding of words and pictures and make a connection between them rather than narration (words) alone.

Contiguity aids assume that presenting analogous narration and animation simultaneously can develop meaningful learning instead of presenting information alone. Experiments have shown that the instantaneous presentation of information visually and verbally can impart an understanding of information among students which leads to better problem solving (Richard E. Mayer et al., 1999; Richard E. Mayer & Anderson, 1991, 1992; Richard E. Mayer & Sims, 1994).

Coherence aids help in making information interesting and concise by eliminating any unneeded elements. Research shows that when presenting a meaningful message, removing extraneous words and sounds will help the learner to associate and comprehend the message better (Richard E. Mayer et al., 2001; Moreno & Mayer, 2000).

Modality aids involve delivering information by narration with animation instead of screen text with animation. Screen text with animation induces competition for visual attention between text and animation. This competition for visual attention creates a split attention effect (Mousavi et al., 1995) which may overload the cognitive system. Experiments have shown better learning outcomes with animation and narration together (Richard E. Mayer & Fiorella, 2014; Richard E. Mayer & Moreno, 1998; Moreno & Mayer, 1999; F. Wang et al., 2020).

Redundancy aids use a similar principle as Modality aids. When concise narration is presented together with concise animation, this facilitates comprehension (R. E. Mayer, 1997a; Richard E. Mayer & Moreno, 2002).

The Cognitive Theory of Multimedia Learning has evidence of its utility for increasing learning (Kuba et al., 2021; Mason et al., 2013), including about risk (Bader & Strickman-Stein, 2003; Wilson et al., 2010). I used it in designing a visualization that uses simultaneous animation and narration to help people understand community immunity.

3.3 Affect Heuristic

To understand the role of emotions in decision making, I have used the Affect Heuristic (Figure 13). This theoretical framework describes the importance of affect, i.e., good/bad emotions or, “a faint whisper of emotion,” (Slovic et al., 2005) that guides a person’s judgment and decisions (Slovic et al., 2007). Affect is an automatic response which humans quickly sense or feel associated with positive or negative stimuli (Slovic et al., 2007).

The central strength of the Affect Heuristic is that it provides an explicit framework for how the experiential system influences decisions via affect and emotions (Slovic et al., 2005). The experiential system encodes reality in images, metaphors, and narratives, to which people have affective (emotional) responses. For example, Denes-Raj and Epstein (1994) surmised that this phenomenon is at the root of ratio bias. Specifically, they showed that people would choose a lottery in which the chances of winning were 5 to 9 in 100 (5-9%) over one in which the chances of winning were 1 in 10 (10%) and posited that an image of winning beans from a bigger jar with more beans conveys a more positive affect than a smaller jar having less beans. Fischhoff and colleagues (1978) showed that perceived risks and benefits relevant to a decision are negatively related. This was further explored by Alhakami and Slovic (1994) who linked this inverse relationship to the strength of positive and negative affect. For example, when considering the risk and benefit associated with a decision option that evokes positive affect, people perceive less risk and more benefit. In other words, people base their decisions not only on what they think but also on how they feel about their options (Alhakami & Slovic, 1994). Loewenstein and colleagues described this as the, “risk as feelings,” framework (G. F. Loewenstein et al., 2001).

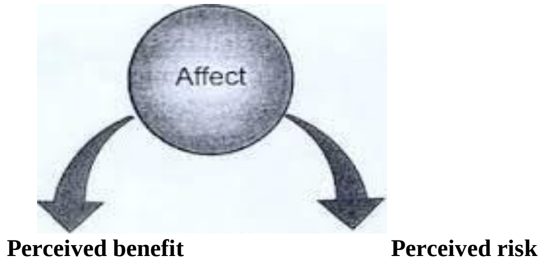

Figure 13: Affect heuristic (Source: Solvic et al., (2002, pp. 397–420))

In my thesis, I used the Affect Heuristic to structure analyses of emotions in response to a visualization, as well as the influence of affect and emotions on attitudes and behavioural intentions towards community immunity.

3.4 Health Belief Model

Of the multiple possible theoretical frameworks available to explain health behaviour, I used the Health Belief Model (Rosenstock, 1974) (Figure 14). The key tenet of this model is the way in which individuals perceive the world and how these perceptions motivate their behaviour (Jose et al., 2021; Wong et al., 2020). The model hypothesizes that the readiness to take action to prevent a disease stems from individuals' perceptions of their susceptibility to disease, the severity of the disease, the level of threat of the disease, and benefits versus barriers to behaviour change.

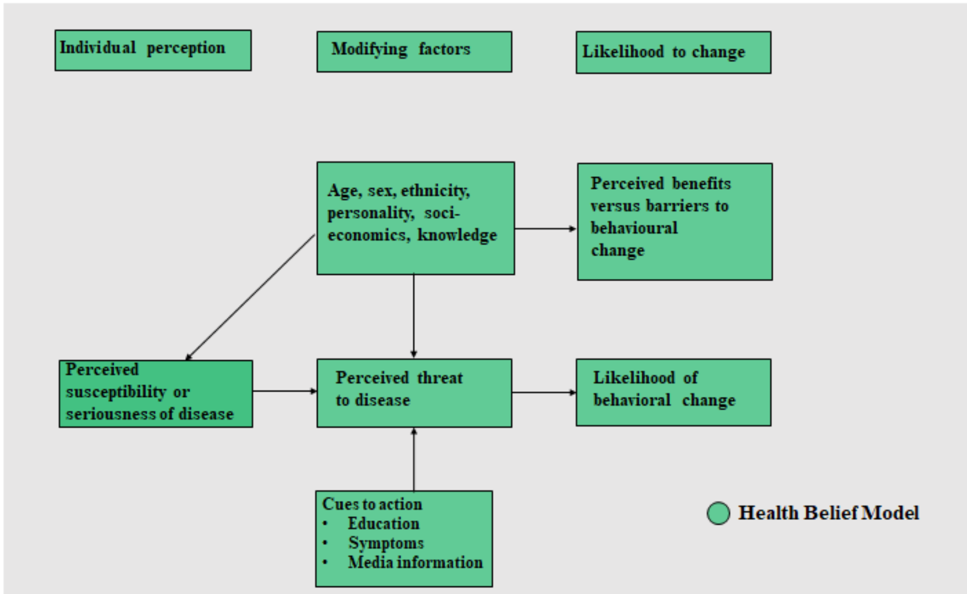

Figure 14: Health belief model (Adapted from: Egger et al., (1999, pp.35))

The Health Belief Model has been applied to predict a wide variety of health-related behaviours such as screening for early detection of asymptomatic diseases and receiving immunizations (Janz & Becker, 1984). Self-efficacy was a subsequent addition to the Health Belief Model. It explains the confidence in one's ability to take action and implement any change in their behaviour. In (1988), Rosenstock, Strecher, and Becker suggested that self-efficacy be added to the Health Belief Model as a separate construct, together with the original concepts of susceptibility, severity, benefits, and barriers (Rosenstock et al., 1988). Self-efficacy had not previously been explicitly incorporated into the early formulations of the model, as it was developed in the context of preventive health action like screening tests or immunization, which were not perceived as complex behaviours at the time.

The Health Belief Model has been most widely applied to a broad range of health-related behaviours (Glanz et al., 2008) to understand preventive and health promotive behaviour (e.g., diet and physical activity) and vaccination uptake (K. M. Corace et al., 2016; Walling et al., 2016). In determining psychological factors, the Health Belief Model helps assist in targeting any inconsistencies with reasoning for not adopting the specific health behaviour in question. Studies have shown that the Health Belief Model allows identification of significant predictors of vaccination (Briones et al., 2012; K. Corace et al., 2013;

Shahrabani et al., 2009; P. J. Smith et al., 2011) which makes it a reasoned choice by researchers aiming to predict vaccine-related behaviours.

3.5 Integrated Conceptual Framework

For this dissertation, I have combined the frameworks described in sections 3.1 to 3.4 into an integrated conceptual framework.

I selected the Health Belief Model as the most likely framework to help me understand potential vaccination behaviour as a result of exposure to the visualization. However, this model hypothesizes that the likelihood of an individual to take action stems from individual perception, and the model offers less detail regarding how such perceptions are shaped by different cues to action. Therefore, I have augmented this model to better understand the antecedents of perception. Gestalt Principles of Visualization guided the design of a visualization. I used the Cognitive Theory of Multimedia Learning to explain cognitive responses to visualizations and the Affect Heuristic to explain emotional responses.

My main interest in this work was in the proximal cognitive and emotional responses to a visualization. I expected that these may influence individual perceptions of risk; i.e. perceived threat or susceptibility to disease, which may likely lead to a change in attitudes and behavioural intentions consistent with the Health Belief Model. Vaccination is a prosocial act. Vaccine coverage (a contributing factor for community immunity) is affected by vaccine hesitancy which is influenced by trust (as discussed in section 1.2.4). Trust plays an essential role in vaccine acceptance through trust in vaccines, healthcare systems, and trust in information provided, which in turn affects health-related decisions. I have incorporated trust in the consolidated framework. Trust offers one of the mechanisms through which emotions influence individual perceptions and decisions (Dunn & Schweitzer, 2005; Robbins, 2016). Although it was not a primary goal of this work, I expected that if people trust information provided and fully understand their role in protecting others through vaccination, it might be possible to change the attitudes and behavioural intentions of vaccine-hesitant individuals. The Integrated Conceptual Framework used in this study is shown in Figure 15.

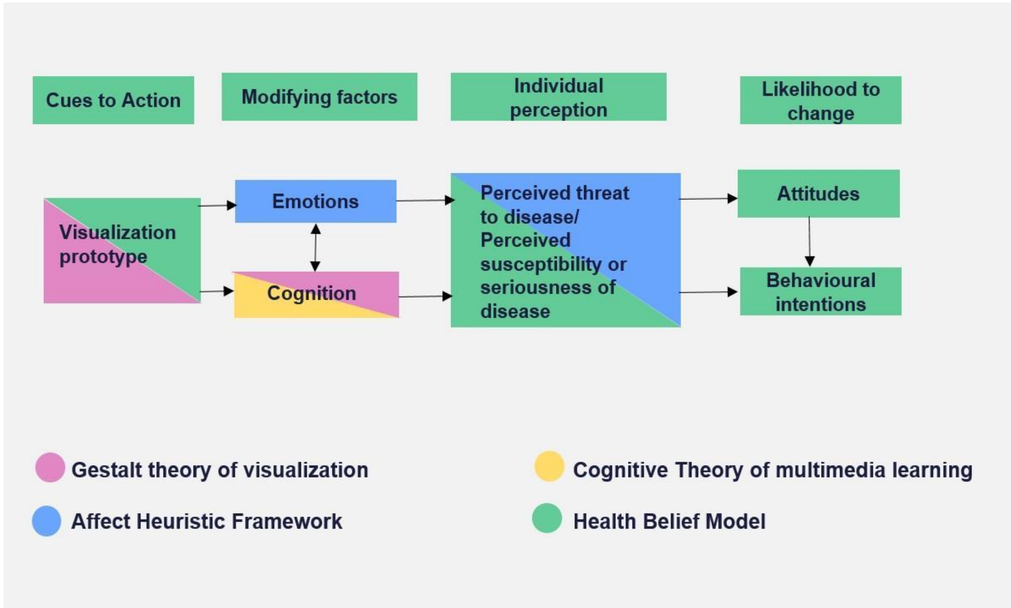

Figure 15: Integrated conceptual framework

Chapter 4: Methodology

4.1 Aim 1: Systematic review

The first aim of my dissertation research was to synthesize the literature on interventions designed to convey the concept of community immunity via a systematic review. In this systematic review, I aimed to synthesize evidence about interventions intended to help members of the general public better understand the concept of community immunity. By interventions, I mean any method, strategy, or tool developed to help people understand the concept of community immunity. Because visualization is a powerful way to convey complex topics (Hawley et al., 2008; Okan et al., 2015) and because visualizations have proved effective at helping members of the public understand other related mathematical concepts such as how population-based statistics apply to an individual (Garcia-Retamero & Cokely, 2011; Hawley et al., 2008), I was particularly interested in web-based visualizations as interventions. The objective of my systematic review was therefore to describe interventions, including web-based interventions, aimed at conveying the concept of community immunity and to describe any reported effects of such interventions.

Search strategy

To identify peer-reviewed literature describing interventions designed to communicate the concept of community immunity, I searched PubMed, EMBASE, CINAHL, the Cochrane Central Register of Controlled Trials, and Web of Science on April 19, 2016, updated on January 25, 2018, to identify any newer articles. The full search strategy is available in Appendix 1. I did not apply any language or publication date restrictions. In addition, I retrieved further studies by searching the references of relevant review articles (Cairns et al., 2012; Crocker-Buque et al., 2017; Dubé, Gagnon, et al., 2015; Jarrett et al., 2015; Jordan et al., 2006; Kaufman et al., 2013; Lorini et al., 2018; Odone et al., 2015; Sadaf et al., 2013; Saeterdal et al., 2014), by a hand search of articles cited by or cited in the included articles, and by consulting with 33 experts through professional networks of myself and co-authors for suggestions of relevant published or unpublished literature or web based interventions missed during the search.

To identify interventions that may not have associated publications, I conducted an online Google search in two stages. I sought any web-based representations conveying the concept of herd immunity or community immunity. First, on April 24, 2017, I conducted a standard search using Google to find web-based representations which had herd immunity components or were about explaining community immunity. I used six search terms ‘‘Herd immunity”, ‘‘Herd protection”, ‘‘Herd effect”, ‘‘Community protection”, ‘‘Indirect protection”, ‘‘Community immunity” combining each with, ‘‘AND (simulation OR animation OR visualization)”. I reviewed the first 30 results for each search, as it is rare for users to click past the third page of ten search results per page, and therefore, researchers analyzing medical content available on the web often use 30 as a threshold (Hargrave et al., 2006; Petrescu, 2014; van der Marel et al., 2009). On June 9, 2017, I conducted the same searches in private browsing mode to ascertain whether my results had been affected by a ‘‘filter bubble” (Resnick et al., 2013); that is, the way Google search results are adapted to one’s previous browsing activity.

Study selection and screening process

I and another trained reviewer independently identified and screened all studies and web-based interventions for their eligibility. Conflicts were resolved by a third reviewer. I used PICO (Population, Intervention, Comparison, and Outcome) to structure study inclusion and exclusion criteria. The population of interest was the general public or any subgroup thereof. I sought studies describing any strategies, tools or methods (including campaigns and educational tools) designed to help people understand more about the concept of community immunity. My comparator was any control, including offering no education about community immunity or comparing participants before and after an intervention. The outcomes of interest included common outcomes in vaccination acceptance studies: knowledge (comprehension, understanding), attitudes (attitudes toward or against vaccination), beliefs (risk perceptions, perceived benefits), and behavioural intentions (intentions to be vaccinated or not). I also sought to extract any data about emotions (e.g., fear, anxiety). As previously discussed in section 1.2.6, emotions are key drivers of decisions (Slovic et al., 2007).

I excluded studies that did not have a component specifically about community immunity; for example, studies about policies, policy decision-making, vaccine provision programs, vaccine hesitancy, or anti-vaccine movements. For web-based tools, my inclusion and exclusion criteria used the same specifications regarding population and intervention. I did not apply comparison and outcome criteria to web-based tools because my team and I did not expect these to report evaluation studies. I report this review according to PRISMA guidelines (see PRISMA checklist in Appendix 2). This systematic review was registered in PROSPERO (CRD42017069206).

Data extraction

Two people independently extracted data from included articles and web-based interventions. Conflicts were resolved by a third reviewer (supervisor). From included articles and web-based interventions, I extracted information about: (1) the type of intervention (educational material for home use, live education session, etc.) (2) the medium of the intervention (paper, web, etc.), (3) the objective of the study or intervention, (4) whether the intervention was solely about community immunity or whether it was a broader intervention, (5) whether the intervention aimed to convey the importance or existence of community immunity (the ‘‘what” of community immunity; i.e., the existence of community-level protection to safeguard those who are not immune), how it works (the ‘‘how” of community immunity; i.e., community immunity is achieved by preventing the spread of infection from one person to another within the community), or both. For evaluated interventions, I extracted (6) the characteristics of study participants and (7) outcomes observed. I extracted data about interventions’ effects on knowledge, attitudes, beliefs (perceived benefits, perceived risks), and behaviours. I pre-selected these outcomes based on the Health Belief Model (Janz & Becker, 1984; Rosenstock, 1974), a model widely used to predict health related-behaviours and to assess outcomes in studies of interventions about vaccination and immunization (Cairns et al., 2012; Dubé, Gagnon, et al., 2015; Kaufman et al., 2013; Saeterdal et al., 2014). People may also rely on emotional, cultural, and social factors before making a decision about vaccination (Dubé et al., 2013; Hobson-West, 2003). Cultural and social factors are unlikely to be changed by interventions, but emotions may be affected. Therefore, I also extracted data about emotions elicited by interventions based on the Affect Heuristic theoretical framework (Slovic et al., 2007). Because I sought to understand all possible effects, I did not prespecify any of these as a primary outcome.

Data validation

When there were missing details or were uncertain about data, I contacted authors to review the data extracted about their studies. I contacted four authors via email. I received responses from three of these four, who reviewed the draft extractions I had sent as well as provided us with additional data not reported in their publication. After a reminder email with no response, I also followed up with the nonresponding author and their co-authors by email and phone, but was not able to reach any member of the authorship team.

Quality assessment

I used the Mixed Methods Appraisal Tool (MMAT) by Pluye and colleagues (Pluye et al., 2009) to assess the quality of all studies. Quality assessment was conducted independently by myself and another trained reviewer, with disagreements settled through discussion until consensus was reached. Remaining conflicts were resolved by a third reviewer (my thesis supervisor).

Data synthesis

I organized data in tables and synthesized it descriptively. My team and I also calculated observed heterogeneity (Higgins I^2) to determine whether it would be possible to conduct meta-analyses of available randomized controlled trials (Betsch et al., 2013, 2017) on common outcomes, namely, behavioural intentions, perceived risk of disease, and perceived risks of vaccination. We used package meta version 4.4.0 (A. Tran, 2014) within R version 3.3.0 (R Development Core Team, 2017) for these calculations.

4.2 Aim 2: Prototype development

In the second aim of this study, I sought to iteratively develop an application about community immunity that would be understood by people with varying levels of education and to assess and optimize people's cognitive and emotional responses to the application. My focus included emotions because, as previously discussed in section 1.2.6 emotions influence people's decisions (Bechara & Damasio, 2005; Keltner et al., 2013; So et al., 2015), including health decisions (Ellis et al., 2018; Revenson & Pranikoff, 2005; Zikmund-Fisher et al., 2010), and specifically vaccination decisions (Dubé et al., 2013; Tsuda & Muis, 2018).

I aimed to determine (1) whether and how people attend to different visual elements to explain the concept of community immunity (what is community immunity and how it works), (2) whether these elements are understandable, and (3) whether people understand how community immunity safeguards people, especially vulnerable populations who cannot be vaccinated or who may not respond to vaccines owing to their age or suppressed immune system.

Ethics Approval and Consent to Participate

This project was approved by the 'Comité d'éthique de la recherche en sciences de la santé' ethics committee of Laval University (approval no: 2017-137 R-2/15-07-2019). All participants provided informed consent in writing.

Concept Map

Before designing the first prototype, I and my multidisciplinary team began by developing a concept map (N.-S. Chen et al., 2008) of what the prototype should convey (Appendix 3). Concept maps are tools for organizing and representing knowledge (Novak, 1993) or graphical representations of different concepts and the relationships between those concepts (Plotnick, 1997). My concept map was used to organize the underlying content presented in the visualization within three major themes: (1) community, (2) infection, and (3) vaccines. I expanded and refined the components of each theme throughout the study in response to participants' feedback. The theme *community* included content about how a community is made up of individuals, including vulnerable people living among other individuals. The theme *infections* included content about how different pathogens cause different infections and spread at different rates. The theme *vaccines* included content about how effective vaccines may or may not be, how some vaccine effectiveness may wane over time, and how different diseases require different vaccine coverage to prevent the spread of infection and to create community immunity.

Overall Approach

I developed my prototype application according to the concept map and predefined communication goals for each element of the prototype. Each element of the prototype was linked to what it was intended to convey in the concept map, and what cognitive and/or affective (emotional) responses I aimed to evoke among participants. Across multiple iterations (Appendices 4-7), I then measured participants' responses to assess the extent to which each element of the application met its associated communication goals. In each cycle, I further sought to understand participants' needs, strengths, and limitations; observe how they attended to visual elements and colors; and identify potential improvements that could be made to the application.

Framework

To design the application and interpret people's responses, I used my integrated conceptual framework (section 3.5). My guiding methodological framework was that of a user-centered design (Witteman, Dansokho, Colquhoun, et al., 2015) in which potential users are consulted early and often, with their responses to prototype versions serving to help guide iterative improvements of the intervention or tool.

Study Participants and Setting

Across all four study cycles, I recruited participants who were aged 18 years or older, had either no vision problems or corrected vision problems (e.g., using eyeglasses or contact lenses), and were able to provide written informed consent, read and understand French or English, and use computers. In cycles 1, 3, and 4, I recruited participants to come to our university-based human-computer interaction laboratory by sending invitations to a university-wide listserv directed at all students, staff, and others. In cycle 2, I recruited participants in person by approaching them at a university-based cafeteria. In cycle 3, in addition to the listserv recruitment, my team and I also recruited participants in person at a public library and two shopping malls located in areas of the city whose postal codes are associated with more diverse educational backgrounds. An incentive of either Can $10 (US

$7.46; cycles 1, 2, 4) or Can $20 (US $14.92; cycle 3) was offered for their time and any transportation costs incurred. In cycle 3, we offered a larger incentive because, after viewing my visualization, participants subsequently interacted with materials developed for other studies, meaning that the individual sessions took more time.

Psychophysiological Measurement

Design cycles 1, 3, and 4 used four psychophysiological data collection methods: eye tracking, galvanic skin response, electroencephalogram (EEG), and facial emotion recognition. I used eye tracking to determine what people were looking at and to measure participants' visual attention (Kessler & Guenther, 2017). I used galvanic skin response to determine when participants experienced peaks in emotional arousal (Nepal et al., 2018). Such peaks indicate instances of strong emotions. I expected the visualization to elicit strong emotions when, for example, something alarming happened, such as a vulnerable person getting infected with a contagious disease. I used facial emotion recognition software to assess emotional valence (ie, whether emotions were positive or negative) (Fish & Griffin, 2019). I expected participants' emotions to be positive when the visualization depicted positive things happening, for example, community immunity being achieved and protecting community members, and to be negative when the visualization depicted negative things happening, for example, an infection spreading in the community. I used EEG to assess participants' cognitive workload and engagement while looking at the information provided in the visualization (Hu et al., 2017). I aimed for participants to experience higher engagement when interacting with the visualization without exceeding a cognitive load threshold above which they might be less likely to process new information.

Apparatus and Procedures

As shown in Figure 16, participants sat in a stationary chair in front of a desk with a mobile eye tracker (Tobii X2-30) and a webcam mounted on the computer monitor, a keyboard, a mouse, and computer speakers. A member of the research team explained each participant-worn device while placing it. These participant-worn devices were a portable galvanic skin response apparatus (Shimmer Sensing Shimmer3 GSR+) worn on the participant's nondominant hand and an EEG (Advanced Brain Monitoring B-Alert X-Series) fitted on the participant's head, using a gel on the electrodes. I followed standard procedures for each device’s calibration (IMotions, 2016; Krafka et al., 2016; Matsumoto & Ekman, 2008; Shimmer, 2013). Data streams for all devices were synchronized and saved using the iMotions Attention Tool version 7 (cycle 1) or version 8 (cycles 3 and 4) (*Press & Media Resources - iMotions*, accessed 2020).

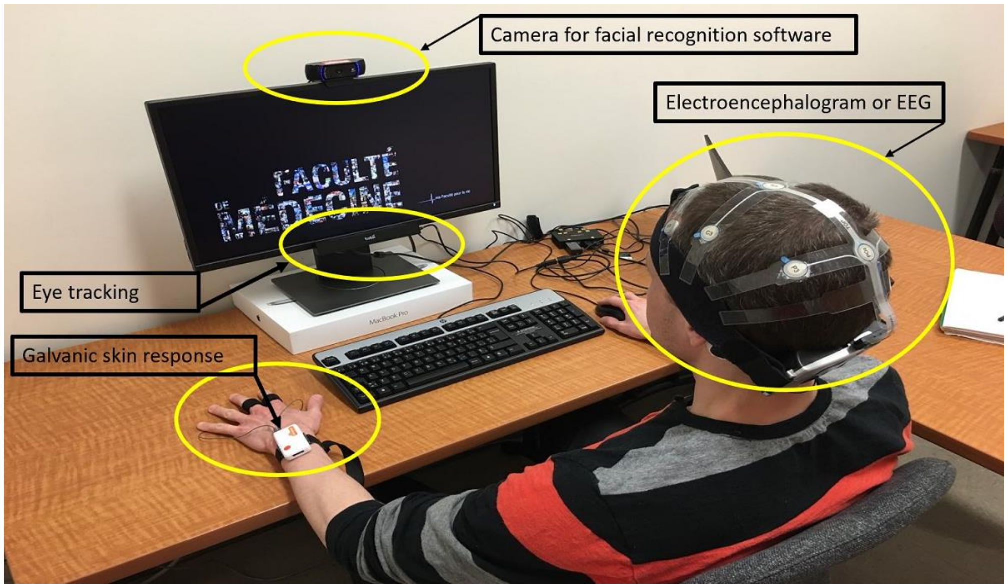

Figure 16: Human-computer interaction laboratory apparatus.

Verbal Feedback

I complemented psychophysiological data on participants’ nonverbal reactions with brief verbal feedback. Using semi structured interview questions (Appendices 8-10), I or a student research assistant asked participants to summarize in their own words what they saw in the visualization, what message it aimed to convey, and anything they found confusing or unclear. They were also asked questions about how to improve the visualization or personalized avatar building. If their explanation about the visualization indicated that they may have missed some visual elements, I probed for more specific information on how to improve those visual elements. I recorded responses using an audio recorder and took notes. Table 1 shows the summarized study design.

Table 1: Summarized study design

Cycles	Study setting	Sample size	Method for data collection

First cycle	University-based human-computer interaction laboratory via university-wide listserv (email)	n=8	Psychophysiological measurement and verbal feedback
Second cycle	University-based cafeteria (by approaching them)	n=11	Verbal feedback
Third cycle	. University sample: university-based human-computer interaction laboratory via university-wide listserv (email) . Community sample: a public library and two shopping malls (by approaching them)	• University sample: n=49 • Community sample: n=34	Psychophysiological measurement and verbal feedback
Fourth cycle	University-based human-computer interaction laboratory via university-wide listserv (email)	n=8	Psychophysiological measurement (eye-tracking only) and verbal feedback

Analysis

My analytical aim was to assess whether the application achieved its communication goals. To analyze psychophysiological measurements, I examined participants' reactions to each element according to its associated communication goal. I first identified the periods of each element in the visualization according to the voice-over timing. I assessed whether the participant was visually attending to each element by defining an area of interest for each element (e.g., a rectangular region around a symbol) and examining whether the participant had any eye fixations of 200 ms or more in that area of interest. Fixations are described in the literature as lasting from 100 to 500 ms (Bojko, 2013; Mele et al., 2019), 150 to 600 ms (Duchowski, 2007), or as low as 100 ms but typically 200 to 600 ms (Holland, 2019). I selected 200 ms to maximize the likelihood of detecting fixations among people viewing a rapidly moving visualization while avoiding contaminating my data with shorter pauses in eye movement that might not indicate the person extracting any visual information. During the times when the element was present, I then also examined galvanic skin response, facial emotion, and EEG data as predefined for each communication goal. To analyze the galvanic skin response, I used an algorithm to detect peaks in arousal (*Shimmer Sensing, 2013*). Previous literature suggests that this algorithm performs well in detecting such peaks (Akash et al., 2018; Muller et al., 2017). To account for known lags in galvanic skin response (ie, the fact that skin response lags behind experience of heightened arousal by 3 to 5 seconds (Terkildsen & Makransky, 2019)), I inspected data for peaks in arousal during the defined time for each communication goal and for an additional 5 seconds afterward. The existence of such peaks would indicate that the participant experienced a heightened emotion of some kind while that element was displayed. For instance, in the first cycle, some participants showed a peak in arousal when the visualization showed vulnerable people getting infected. To analyze facial emotions, I used the facial recognition software FACET (Emotient) within the iMotions Attention Tool (IMotion, 2016). This software uses algorithms to translate the movement of facial features, such as eyes, eye corners, brows, mouth corners, and nose tip, into classifications of emotional valence. Recent work suggests that this automated facial-expression analysis software performs well for detecting emotional states (González-Rodríguez et al., 2020; Stöckli et al., 2019). I inspected the aggregated data for the number of occurrences across all respondents, and for any positive, negative, or neutral emotional valence elicited by the visualization. To analyze the EEG data, I used algorithms to estimate participants' cognitive workload and engagement (IMotions, 2016). Cognitive workload indicates the extent to which working memory is being used. Engagement indicates a participant's attentiveness while watching the visualization. Previous studies have validated these algorithms for measuring cognitive workload and engagement (Berka et al., 2004, 2007; Ortiz de Guinea et al., 2013). Cognitive workload is reported on a continuous scale from 0 to 1, with 0 to 0.4 classified as boredom, 0.4 to 0.7 as optimal workload, and 0.7 and above as information overload. Engagement levels are also reported on a continuous scale from 0 to 1, with 0 to 0.1 classified as sleepiness and drowsiness, 0.3 as distraction, 0.6 as low engagement, and 0.6 to 1 as high engagement. A summary score was computed by averaging values for each communication goal across all participants. For cycles with fewer than 10 participants, I examined emotional valence and EEG data at the individual level only. For cycles with 10 or more participants, to summarize data while continuing to weigh data from each participant equally, I calculated the mean valence, cognitive load, and engagement for each participant for each element, and then computed summary statistics and indices of dispersion across all participants. When these mean values were normally distributed across participants, my summary statistic was a global sample mean and my index of dispersion was a sample SD. When these mean values were skewed across participants, my summary statistic was a global sample median, and my index of dispersion was an IQR. In addition to analyses by area of interest, I also inspected the heat maps of full screens. Heat maps are visual representations of data showing the relative intensity of participants' visual attention to see where participants are looking at the most.

To analyze verbal feedback, two independent analysts (myself and another study team member) examined the responses independently and assessed the extent to which responses aligned with communication goals for each cycle by deductively comparing participant responses to my detailed concept map. Any disagreement was resolved through discussion with the senior researcher (my thesis supervisor). I noted anything that failed to align with communication goals or was confusing to participants to guide changes for the next cycle. After collecting data for each cycle, I compiled and reviewed data with two team members, summarized problems, and drafted recommendations. These recommendations were then discussed with the senior researcher (my thesis supervisor) and, when necessary, the larger team to determine changes for the next cycle.

Iterative Cycles

First Cycle

Our multidisciplinary team developed the first version of a visualization based on epidemiological evidence that we had organized in the concept map. We prespecified communication goals for different visual design elements (ie, what we wanted to convey with each element of the visualization and how we expected people to respond). We used four devices (see Figure 16) and brief verbal feedback (audio-recorded) to assess participants' interpretations and reactions to the content of the visualization. After viewing, the participants described the visualization in their own words. They were also asked the following questions: What do they think this visualization wants to convey? Is there anything in the visualization that they find unclear or confusing?

Second Cycle

We developed a revised version of the visualization based on participants' feedback in the first cycle. We predefined our communication goals for the second cycle (Appendix 11) and refined the concept map by adding how different diseases spread differently (pertussis, measles, and influenza as test case) and that different diseases require a different number of vaccine doses (e.g., a single dose, multiple, booster, or annual doses). The visualization showed how different parameters (e.g., vaccine coverage and intra community contact) can influence community immunity. We audio-recorded a brief verbal feedback.

Verbal Feedback

In this cycle, we only used audio-recorded verbal feedback (no psychophysiological measurements were used in this cycle (Table 1) to assess participants' interpretations of the visual content and their suggestions to improve it. We chose this method to increase the richness of verbal responses for each visual element. We asked participants to describe their understanding of the visualization, how vaccines work to protect people from diseases, what it means to be immune, and if there was anything confusing or unclear in the visualization. We showed images from the visualization to participants and asked specific questions (e.g., what do the icons of the older woman and the baby represent in this visualization? What do the images of viruses causing different diseases represent?). We also asked participants about different terms used to explain community immunity, that is, herd immunity, community immunity, and community protection and which term they prefer.

Third Cycle

We developed a third version of a visualization based on participants' feedback in the second cycle. We used the same techniques as in the human-computer interaction laboratory described earlier, along with verbal feedback. The third cycle was tested in two different settings: a university and different locations in a community setting (two shopping malls and a public library). We predefined the communication goals for the third cycle (see Appendix 12 for university sample and Appendix 13 for community sample). We asked participants to describe, in their own words, the visualization shown to them. We included a larger number of participants in this cycle, as our visualization was closer to launch and we wanted to make sure that it was easily understood and that people grasped the concept of community immunity. We also wanted to test if our communication goals were achieved among people with varied levels of education.

Fourth Cycle

By the fourth cycle, the content of our visualization had achieved nearly all predefined communication goals. However, one major issue remained. Up to this cycle, we had used generic avatars in our visualization. On the basis of data from previous cycles, we were concerned about the extent to which people could identify with the generic avatars presented in the visualization. Therefore, we developed an additional piece in which people were asked to build their own communities by making personalized avatars (their own, 2 vulnerable people in their community, and 6 avatars of people around them who could be family members or coworkers). We added this feature so that people could better identify with the avatars that were subsequently integrated into our application to explain community immunity. We asked participants to provide critical feedback on the process of creating their own avatars and building their own communities. In this cycle, we focused on three questions related to the new features: (1) Was an onboarding tutorial describing how to build avatars a useful addition? (2) Was it easy to build the avatars? and (3) Was the length of the avatar-building process reasonable? We further asked what participants thought of the avatar-building options, including the accessories and color palettes for skin tone and hair color. Participants also described the application in their own words. We only used the eye-tracking device in this cycle to assess visual attention.

4.3 Aim 3: Evaluating prototype

The third and last aim of this dissertation was a multi-armed factorial randomized controlled trial. The primary objective was to see the potential robustness of my intervention (Herdimm) vs control (no education about community immunity), I assessed its effects across four possible diseases (measles, pertussis, flu/influenza, and an undefined vaccine-preventable disease, hereby referred to as "generic"). I tested the intervention across diseases since disease transmission dynamics and herd immunity parameters differ across vaccine-preventable diseases and it was important to assess whether any potential effects would be robust and would generalize across different infectious diseases. For generic, I used the visualization for measles, but did not specify the disease and merely referred to, "a vaccine-preventable disease," in all questions. My first and second research questions were therefore:

> *"Across 4 vaccine-preventable diseases, does the Herdimm intervention influence risk perception compared to a control (no intervention)?" (research question 1)*

and,

> *"Across 4 vaccine-preventable diseases, does the Herdimm intervention influence other outcomes (5C scale, emotions, trust, knowledge, vaccination intentions, COVID-19 vaccine intentions) compared to a control (no intervention)?" (research question 2)*

My secondary objective was to compare the effects of disease-specific versions of my intervention to the effects of disease-matched interventions (comparators). I did this because it was important to determine the effects of my intervention compared to existing interventions available online. My third research question was therefore:

> *"For any of the 4 diseases, how do effects of the Herdimm intervention compare to those of existing interventions already available online?" (research question 3)*

Comparators were all existing applications (i.e., interactive online tools that include visualizations) and visualizations (i.e., videos or gifs) available online that I had identified in my systematic review or in my ongoing collection of available applications and visualizations. Links to comparators are included in Table 8.

I developed the Herdimm application in both official languages (English and French) of Canada. The trial was conducted in both languages; however, not all comparator materials were available in both languages (see Table 8 and Appendix14 for links to all videos or websites). I therefore used slightly different randomization patterns for English- and French-speaking participants (Figure 17, Section Randomization).

Ethics and trial registration

My study was approved by the ethics committee of Laval University. I pre-registered the trial (ClinicalTrials.gov identifier: NCT04787913) and study materials (protocol, study questionnaire, data dictionary, and pre-scripted statistical code developed with simulated data prior to beginning the trial on February 26, 2021) are available on Open Science Framework: (https://osf.io/hkysb/ Note: this has not been published yet). I report the trial following the CONSORT guidelines (*The CONSORT Statement*, accessed 2021). The trial ran from March 1, 2021 to July 1, 2021.

Context and study participants

The study was conducted among adults living in Canada. We deployed the online randomized controlled trial in Qualtrics, online survey software. Participants were recruited using established survey panels (subcontracted in Qualtrics). Participants were eligible if they were 18 years and above, residing in Canada, able to use a computer, could read and understand French or English, and were able to provide consent. Those who didn't meet these criteria were excluded from the study. We aimed to recruit a minimum of 25% of the sample as French speakers (compared to English speakers). A small incentive (typically $1-1.50, depending on panel) was offered to the participants to complete the survey.

Interventions

My main intervention was the Herdimm application. The main purpose of the Herdimm application was to convey the concept of community immunity to people across varying levels of education. My primary objective for the study evaluating the application was therefore to assess the application's effects on participants' risk perception. My secondary objectives were to assess other cognitive and emotional responses to the application.

Outcomes

My primary outcome was risk perception, defined for this study as the participants' sense of risk posed to an individual, their family, their community, and vulnerable people in their community. Secondary outcomes were measures of vaccination intentions, trust in the information provided, emotions, knowledge about community immunity, and a validated scale of antecedents of vaccination (5C scale (Betsch et al., 2018)). Measurement of each of these is described in more detail in the section 'Dependent variables' below.

Variables: Dependent variables

I evaluated the outcomes using ad hoc questions developed with the help of a team of colleagues who are experts in the fields of risk communication, decision making and immunization to assess risk perception, vaccination intentions, trust in the information provided, emotions, and knowledge about community immunity and a five-factor, 15-item validated scale measuring psychological antecedents of vaccination (Betsch et al., 2018). I pre-tested all items' clarity during Prototype development (see section 4.2 Aim2: Prototype development), leading us to adapt the wording of one item in the validated 5C scale. Specifically, I changed, "When everyone is vaccinated, I don't have to get vaccinated, too." to, "When everyone else is vaccinated, I don't have to get vaccinated too." Tables 2, 3, 4, 5, 6, and 7 below provide item wording and response options for these variables. Appendix 15 provides the complete questionnaire.

Table 2: ***Risk perception***

Risk perception	
Items	**Response options**
1. Imagine there are two groups of 100 people each. In one group, there is 1 UNvaccinated person surrounded by 99 vaccinated people. In the other group, there is 1 vaccinated person surrounded by 99 UNvaccinated people. Who is at higher risk of getting infected with {{measles/pertussis/the flu/a vaccine preventable disease}}?	Left: The 1 UNvaccinated person surrounded by 99 vaccinated people is at higher risk. (value: 0) Middle: They are both equally at risk. (value: 50) Right: The 1 vaccinated person surrounded by a group of 99 UNvaccinated people is at higher risk. (value: 100)

2. A person's decision to be vaccinated or not against {{measles/pertussis/the flu/a vaccine preventable disease}} affects only them, individually.	1 = strongly disagree 2 = moderately disagree 3 = slightly disagree 4 = neutral 5 = slightly agree 6 = moderately agree 7 = strongly agree
3. People who are vaccinated against {{measles/pertussis/the flu/a vaccine preventable disease}} are less likely to pass it on to others.	1 = strongly disagree 2 = moderately disagree 3 = slightly disagree 4 = neutral 5 = slightly agree 6 = moderately agree 7 = strongly agree
4. My decision to be vaccinated against {{measles/pertussis/the flu/a vaccine preventable disease}} **has no impact** on anyone else's chances of catching {{measles/pertussis/the flu/that vaccine preventable disease}}	1 = strongly disagree 2 = moderately disagree 3 = slightly disagree 4 = neutral 5 = slightly agree 6 = moderately agree 7 = strongly agree
5. My decision NOT to be vaccinated against {{measles/pertussis/the flu/a vaccine preventable disease}} has no impact on anyone else's chances of catching {{measles/pertussis/the flu/that vaccine preventable disease}}	1 = strongly disagree 2 = moderately disagree 3 = slightly disagree 4 = neutral 5 = slightly agree 6 = moderately agree 7 = strongly agree
6. If I get vaccinated against {{measles/pertussis/the flu/a vaccine preventable disease}}, it lowers the risk of vulnerable people in my community (babies, young children, older people, cancer patients) getting sick.	1 = strongly disagree 2 = moderately disagree 3 = slightly disagree 4 = neutral 5 = slightly agree 6 = moderately agree 7 = strongly agree

Table 3: ***Emotions***

Emotions	
Items	**Response options**
1. I am worried about getting {{measles/pertussis/the flu/a vaccine preventable disease}}.	1 = strongly disagree 2 = moderately disagree 3 = slightly disagree 4 = neutral 5 = slightly agree 6 = moderately agree 7 = strongly agree

2. I am worried about people in my life (family, friends) getting {{measles/pertussis/the flu/a vaccine preventable disease}}.	1 = strongly disagree 2 = moderately disagree 3 = slightly disagree 4 = neutral 5 = slightly agree 6 = moderately agree 7 = strongly agree
3. I am worried about vulnerable people in my community (babies, young children, older people, cancer patients) getting {{measles/pertussis/the flu/a vaccine preventable disease}}.	1 = strongly disagree 2 = moderately disagree 3 = slightly disagree 4 = neutral 5 = slightly agree 6 = moderately agree 7 = strongly agree
4. I would feel guilty if someone in my life (a family member, a friend) got the {{measles/pertussis/the flu/a vaccine preventable disease}} from me.	1 = strongly disagree 2 = moderately disagree 3 = slightly disagree 4 = neutral 5 = slightly agree 6 = moderately agree 7 = strongly agree
5. I would feel guilty if a vulnerable person (a baby, a young child, an older person, a cancer patient) got {{measles/pertussis/the flu/a vaccine preventable disease}} from me.	1 = strongly disagree 2 = moderately disagree 3 = slightly disagree 4 = neutral 5 = slightly agree 6 = moderately agree 7 = strongly agree

Table 4: ***Knowledge***

Knowledge	
Items	**Response options**
1. When a person gets vaccinated, it can help protect: (check one)	1= The person (incorrect) 2= The people around them (incorrect) 3= Vulnerable people in their community (incorrect) 4= All of the above (correct)
2. Which people are considered more vulnerable to contagious diseases, either because they can catch them more easily, or the diseases can make them sicker? (check all that apply)	1= People who are very old (correct) 2= People who are very young (babies, etc.) (correct) 3= People who are athletes 4= People who have cancer (correct) 5= People who are healthy adults

3. {{A vaccine preventable disease/measles/pertussis/the flu}} can spread from one person to another person.	1= True (correct) 0= False 77= I don`t know
4. When you come into contact with someone who is infected with {{a vaccine preventable disease/measles/pertussis/the flu}}, there is a chance you could get the disease.	1= True (correct) 0= False 77= I don`t know
5. The only way to get {{a vaccine preventable disease/measles/pertussis/the flu}} is to touch someone who has the disease.	1= True 0= False (correct) 77= I don`t know
6. {{A vaccine preventable disease/measles/pertussis/the flu}} always spread through groups of people at the same speed.	1= True 0= False (correct) 77= I don`t know
7. Some vaccines provide less protection than others.	1= True (correct) 0= False 77= I don`t know
8. Every vaccine provides full protection from a single dose (one needle/shot, one dose of drops in the mouth, or a one spray up the nose).	1= True 0= False (correct) 77= I don`t know
9. Some vaccines only provide partial protection after one dose and require multiple doses to get protected.	1= True (correct) 0= False 77= I don`t know
10. Some vaccines become less effective over time and need booster doses.	1= True (correct) 0= False 77= I don`t know
11. Community protection (or herd immunity) means everyone in the community has been vaccinated.	1= True 0= False (correct) 77= I don`t know
12. Unvaccinated people in a population can be protected from infections when enough people in their community are vaccinated.	1= True (correct) 0= False 77= I don`t know
13. Every person in a community (100%) must be vaccinated to achieve community protection.	1= True 0= False (correct) 77= I don`t know
14. The percentage of people (that is, how many members of a community) who must be vaccinated for the community to achieve community protection depends on the disease and the vaccine.	1= True (correct) 0= False 77= I don`t know
15. An individual's decision to get vaccinated or not affects only that individual.	1= True 0= False (correct) 77= I don`t know

Table 5: ***Trust in information***

Trust in information	
Item	**Response options**
1. During your life, you may have seen information about vaccines. Thinking	1 = not at all trustworthy 2 = moderately untrustworthy

about the information you have seen, how trustworthy was it? *(Control)* Earlier, you saw a {{video, website}} about herd immunity. Thinking about the {{video, website}} you saw earlier, how trustworthy was the information in it? *(Interventions)*	3 = slightly untrustworthy 4 = neutral 5 = slightly trustworthy 6 = moderately trustworthy 7 = strongly trustworthy

Table 6: *Vaccination intentions*: Questions about the vaccination intention, 2 about general vaccines and 2 specific for COVID-19 vaccines were developed

Vaccination intentions	
Items	**Response options**
1. To the best of your knowledge, are you already immune to {{measles/pertussis/influenza}}?	1= Yes 0= No 77= I don't know
2. Imagine you were not already immune to {{measles/pertussis/influenza/a vaccine preventable disease}}. If you were eligible to receive a free vaccine against {{measles/pertussis/influenza/a vaccine-preventable disease}}, how likely would you be to get vaccinated?	[slider: 0 = extremely unlikely, I would definitely NOT be vaccinated; 100 = extremely likely, I would definitely BE vaccinated]
3. Have you already received a COVID-19 vaccine this year (between Dec 2020 and now)?	1= Yes 0= No 77= I don't know
4. Assuming you will be eligible to get a COVID-19 vaccine this year, how likely are you to get the vaccine?	[slider: 0 = Extremely unlikely, I will definitely NOT get a COVID-19 vaccine; 100 =Extremely likely, I will definitely get a COVID-19 vaccine]

Table 7: *5C scale:* 15-item validated scale measuring the psychological antecedents of vaccination (Betsch et al., 2018)

5C Scale	
Items	**Response options**
**Confidence; i.e., “trust in the effectiveness and safety of vaccines, the system that delivers them, the policy-makers”* 1. I am completely confident that vaccines are safe. 2. Vaccinations are effective. 3. Regarding vaccines, I am confident that public authorities decide in the best interest of the community.	1 = strongly disagree 2 = moderately disagree 3 = slightly disagree 4 = neutral 5 = slightly agree 6 = moderately agree 7 = strongly agree

**Complacency; i.e., "perceived risks of vaccine-preventable diseases are low and vaccination is not deemed a necessary preventive action"* 1. Vaccination is unnecessary because vaccine-preventable diseases are not common anymore. 2. My immune system is so strong, it also protects me against diseases. 3. Vaccine-preventable diseases are not so severe that I should get vaccinated.	1 = strongly disagree 2 = moderately disagree 3 = slightly disagree 4 = neutral 5 = slightly agree 6 = moderately agree 7 = strongly agree
**Constraints; i.e., "physical availability, affordability and willingness-to-pay, geographical accessibility, ability to understand (language and health literacy) and appeal of immunization service affect uptake"* 1. Everyday stress prevents me from getting vaccinated. 2. For me, it is inconvenient to receive vaccinations. 3. Visiting the doctor's makes me feel uncomfortable; this keeps me from getting vaccinated.	1 = strongly disagree 2 = moderately disagree 3 = slightly disagree 4 = neutral 5 = slightly agree 6 = moderately agree 7 = strongly agree
**Calculation i.e., "individuals' engagement in extensive information searching"* 1. When I think about getting vaccinated, I weigh benefits and risks to make the best decision possible. 2. For each and every vaccination, I closely consider whether it is useful for me. 3. It is important for me to fully understand the topic of vaccination, before I get vaccinated.	1 = strongly disagree 2 = moderately disagree 3 = slightly disagree 4 = neutral 5 = slightly agree 6 = moderately agree 7 = strongly agree
**Collective responsibility i.e., "the willingness to protect others by one's own vaccination by means of herd immunity"* 1. When everyone else is vaccinated, I don't have to get vaccinated, too. 2. I get vaccinated because I can also protect people with a weaker immune system. 3. Vaccination is a collective action to prevent the spread of diseases.	1 = strongly disagree 2 = moderately disagree 3 = slightly disagree 4 = neutral 5 = slightly agree 6 = moderately agree 7 = strongly agree

Independent variables

Visualization:

I named the first independent variable *visualization*. This variable describes the application (i.e., interactive online tool including a visualization) or visualization (i.e., video or gif) to which each participant was randomly assigned. In addition to the control (no education about community community) and Herdimm (primary intervention), there were also 5 comparator visualizations. Table 8 provides brief descriptions; Appendix 14 provides full details.

Table 8: Visualization for the first, second and third research question (Aim 3)

Visualization	Disease	Language(s)	Compared to
*Herdimm: generic vaccine preventable disease, measles, pertussis and flu (Design for Better Health - Community Immunity (ulaval.ca))	Generic vaccine preventable disease, measles, pertussis and flu	English and French	Control (no information about community immunity)
Guardian visualization	Measles	English	Herdimm: measles, English version
Gif by TheOtherEdmund	Measles	English	Herdimm: measles, English version
Robert Koch Institut visualization	Generic vaccine preventable disease	English	Herdimm: generic vaccine preventable disease, English version
SBS News visualization	Generic vaccine preventable disease	English	Herdimm: generic vaccine preventable disease, English version
Public Health Agency of Canada Flu: Don't Pass It On! English: https://www.youtube.com/watch?v=BMMqzzUt80o French: https://www.youtube.com/watch?v=dhCkucMarhA	Flu	English and French	Herdimm: flu, English and French versions

*Link is provided to one version of Herdimm (measles/generic, French, male voice) provided here. All possible Herdimm intervention links are available in Appendix 14.

Disease:

I named the second independent variable *disease*. This variable describes the disease used in both the Herdimm or comparator intervention as well as in all questions asked of study participants. We used 4 possible diseases: measles, pertussis, flu and a vaccine preventable disease referred to as “generic” in this study (see Figure 17). Note that the Herdimm intervention never named a disease neither on the website nor in the narration. The differences between measles, pertussis, and flu were only apparent in the different disease transmission patterns and in the herd immunity threshold used. For the “generic” disease, I used the measles visualization, but all study questions were framed without a named disease. For example, participants assigned to the measles condition were asked, “I am worried about getting measles,” while those assigned to the generic were asked, “I am worried about getting a vaccine preventable disease.”

Note that for my third research question, comparing the Herdimm intervention to existing interventions already available online, the two independent variables collapsed into one because no other existing interventions offered multiple disease versions. Therefore, for ease of statistical coding, when answering the third research question, my team and I renamed the combination of *visualization* and *disease* as *study arm*. In total, there are 13 study arms (see Figure 17) namely: control generic, control measles, control pertussis, control flu, Herdimm generic, Herdimm measles, Herdimm pertussis, Herdimm flu, robert koch generic, sbs news generic, guardian measles, TheOtherEdmund measles, and public health agency canada flu.

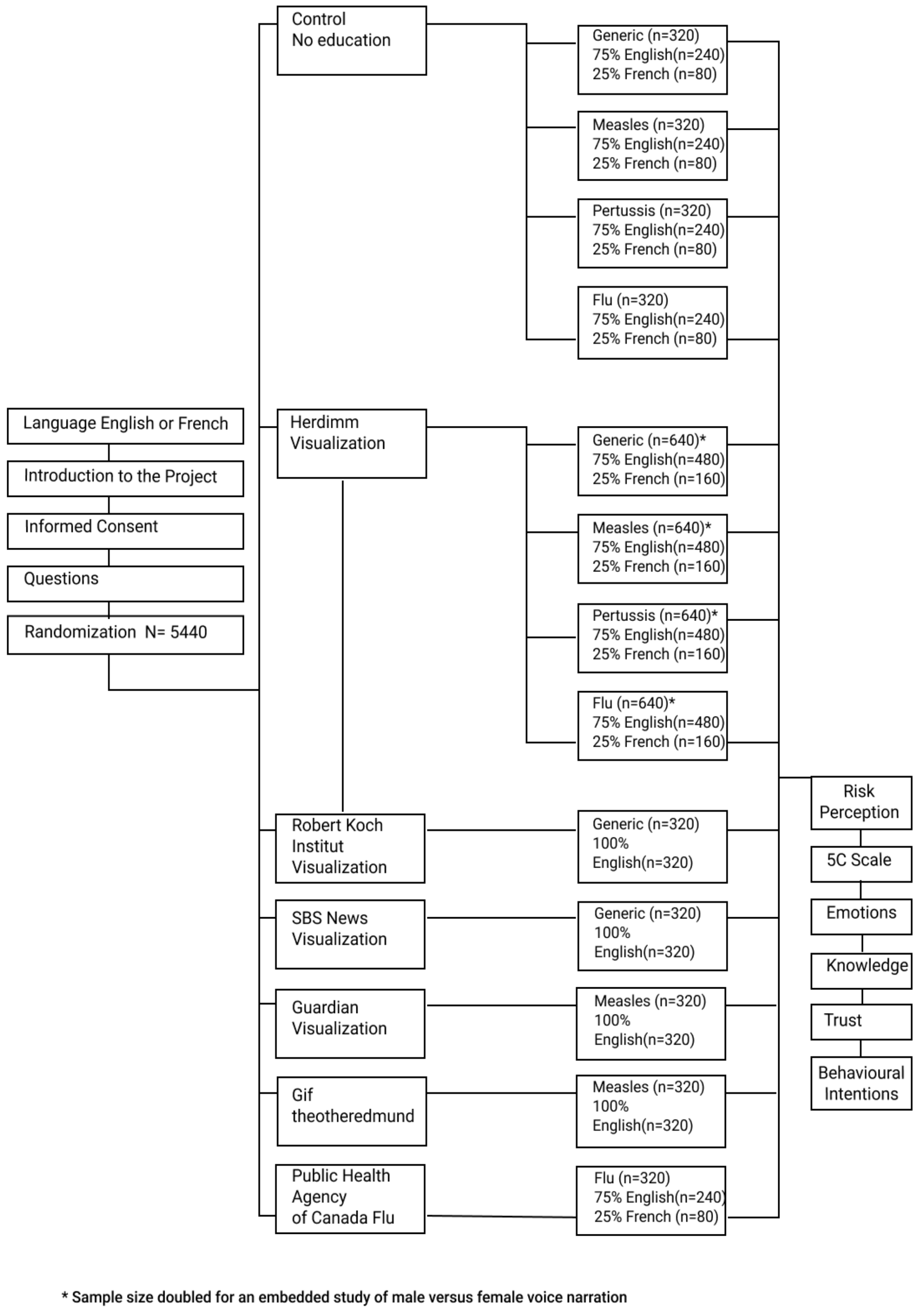

Figure 17: Flow diagram of randomization

Moderating variables

The individual and collectivism scale:

The individual and collectivism scale (Triandis & Gelfand, 1998), also known as cultural orientation scale, measures four dimensions of individualism and collectivism (Table 9). This scale was added to assess whether a person's orientation towards individualism or collectivism might change the effects that the Herdimm application might have affected their risk perception, emotion, knowledge, trust in information and vaccination intention.

Table 9: Individualism and collectivism scale (Triandis & Gelfand, 1998)

Individualism and Collectivism Scale	
Questions	**Response options**
**Horizontal Individualism i.e., "seeing the self as fully autonomous, and believing that equality between individuals is the ideal"* 1. I'd rather depend on myself rather than others. 2. I rely on myself most of the time, I rarely rely on others. 3. I often do "my own thing." 4. My personal identity, independent of others, is very important to me.	9-point Likert-type scale (1 = Never or definitely not; 9 = Always or definitely yes)
**Vertical Individualism i.e., "seeing the self as fully autonomous, but recognizing that inequality will exist among individuals and that accepting this inequality"* 1. It is important that I do my job better than others. 2. Winning is everything. 3. Competition is the law of nature. 4. When another person does better than I do, I get tense and aroused.	9-point Likert-type scale (1 = Never or definitely not; 9 = Always or definitely yes)
**Horizontal Collectivism i.e., "seeing the self as part of a collective but perceiving all the members of that collective as equal"* 1. If a coworker gets a prize, I would feel proud. 2. The well-being of my coworkers is important to me. 3. To me, pleasure is spending time with others. 4. I feel good when I cooperate with others.	9-point Likert-type scale (1 = Never or definitely not; 9 = Always or definitely yes)
**Vertical Collectivism i.e., "seeing the self as a part of a collective and being willing to accept hierarchy and inequality within that collective"* 1. Parents and children must stay together as much as possible 2. It is my duty to take care of my family, even when I have to sacrifice what I want. 3. Family members should stick together, no matter what sacrifices are required. 4. It is important to me that I respect the decisions made by my groups.	9-point Likert-type scale (1 = Never or definitely not; 9 = Always or definitely yes)

Demographics:

This study also used socio-demographic variables as covariates. The socio-demographics were: born in Canada, age, gender, ethnicity, education level, income, disability (any disability and specific disabilities that hamper use of online applications), and preferred language. (Specific question wordings in English and French are available in Appendix 15).

Sample size

To determine the sample size for this between-subjects design, I assumed a small effect size (Cohen's f=0.10) and a statistical test power of 80% (beta = 0.80) and 5% type 1 error (alpha = 0.05), resulting in a required sample size of 320 participants for each arm to run our one-way analysis of variance with three groups. This sample size is also sufficient for one-way ANOVA with more groups, and with two-way ANOVA which requires a smaller sample size per group. The sample size of Herdimm arms were doubled to enable an embedded study (secondary to my thesis) of male versus female voice for the narration. This enabled more precise estimates of the effects of the Herdimm intervention while still maintaining sufficient power to detect differences between, for example, comparator interventions and control. My team and I estimated the sample size by using G*power, version 3.1.9.2 (Faul et al., 2007) for a continuous outcome.

Statistical analysis

First, I performed a descriptive analysis using frequencies and percentages for categorical variables (e.g., born in or outside Canada, language preferred for communicating with healthcare professionals, ethnicity, disability, disability access to technology, sex, gender identity, income, education level), and usual descriptive statistics (mean, standard deviation, median, minimum, maximum) for continuous variables. I performed the descriptive analysis for each variable separately, overall and per study arm. Second, I performed analyses of variance (Scheffé, 1999) to answer my three research questions and determine the effect of independent variables on each dependent variable.

To answer my first research question (*"Across 4 vaccine-preventable diseases, does the Herdimm intervention influence risk perception compared to a control (no* *intervention)?"*), my team and I performed a two-way analysis of variance for continuous variables and logistic regression for dichotomous variables. Variables were transformed from continuous to dichotomous if their distribution did not respect the assumptions of the models described below; for example, if there were ceiling effects and a left-skewed distribution. In such cases, we established thresholds at the median and defined two categories: 1) at or above the median and 2) below the median.

My team and I conducted 5 analyses of variance (5 models) for each outcome. I first determined the direct effects of factors (visualization and disease) without any covariates on risk perception (Model 1). I then examined my planned covariates and removed any containing a category with less than 5% of participants. I used Model 2 to determine the direct effects of factors (visualization and disease) with adjustment for covariates (socio-demographic and individualism and collectivism) (Model 2). Next, I determined the moderating effects of individualism & collectivism with adjustment for socio-demographic covariates (Model 3). Lastly, I examined potential moderation effects of high (college degree and above) or low (no college degree) education levels, without and with adjustment for socio-demographic covariates (Model 4 and 5). This overall approach is summarized in table 10.

Table 10: Model used for analysis

Model	**Analytical goal**
Model 1 (primary model)	Check for direct effects of factors without any covariates
*Model 2	Check for direct effects of factors with adjustment for other covariates (individualism and collectivism, born in or outside Canada, language preferred for communicating with healthcare professionals, ethnicity, disability access to technology, gender identity, income, education level, and age)
*Model 3	Check for moderating effects of individualism & collectivism with adjustment for other covariate (born in or outside Canada, language preferred for communicating with healthcare

	professionals, ethnicity, disability access to technology, gender identity, income, education level, and age)
*Model 4	Check for moderating effects of education level without any covariates
*Model 5	Check for moderating effects of education level with adjustment for other covariates (individualism and collectivism, born in or outside Canada, language preferred for communicating with healthcare professionals, ethnicity, disability access to technology, gender identity, income, education level, and age)

*To see if results are robust when adjusted for covariates or in the presence of moderators.

Throughout the results, I report group-based means with 95% confidence intervals for continuous variables (i.e., *risk perception as feelings, knowledge, emotions*) and probabilities of being at or above the median with 95% confidence intervals for the dichotomous variables (i.e., *risk perception as comprehension, vaccination intentions, COVID-19 vaccine intention, trust in information, and 5C subscales*.)

To answer my second research question (*"Across 4 vaccine-preventable diseases, does the Herdimm intervention influence other outcomes (5C scale, emotions, trust, knowledge, vaccination intentions) compared to a control (no intervention)?"*), my team and I repeated the 5-model analyses as described above, using logistic regression rather than analyses of variance to analyse dichotomous outcome variables.

To answer my third research question ("*For any of the 4 diseases, how do effects of the Herdimm intervention compare to those of existing interventions already available online?"*), my team and I applied a one-way analysis of variance or logistic regression. For this research question, I examined the results of model 1 (primary model) and then also examined the results of model 2 to ascertain whether the findings of model 1 were robust to adjustment for covariates. I then examined the results of models 4 and 5 for possible interactions with education levels. I did not apply model 3 (moderating effects of individualism and collectivism) to this research question because this fell outside the scope of an already extensive analysis. Because the previously existing interventions each only address one disease whereas Herdimm was built to explicitly represent the epidemiology of multiple vaccine-preventable infectious diseases, I compared relevant study arms for one disease at a time (see Table 8) and could not use disease as an independent variable.

Following analyses of all three research questions, to address missing data, my team and I also re-ran all the primary models for outcomes which had missing values. To do this, fifteen multiple imputation datasets were generated. We examined whether results with imputed data replicated or contradicted our earlier findings.

My team and I performed all analyses using R version 4.1.0 (R Development Core Team, 2017). We used the package psych (version 1.9.12.31) (Revelle, 2017) for descriptive analyses, the packages car (version 3.0-8) (J. Fox & Weisberg, 2018) and emmeans (Lenth, 2021) for the analyses of variance and the package mice (version 3.11.0) (van Buuren & Groothuis-Oudshoorn, 2011) for multiple imputation. I developed statistical code with the support of a statistician and thesis supervisor, using simulated data. An external statistician peer reviewed the R code and returned comments on November 30, 2020.

Randomization

I used computerized randomization within Qualtrics to automatically assign participants to study arms randomly. Because some of my planned comparisons were only possible in English, not French, I pre-specified the randomization such that when a study arm was accessible in both languages, 75% of the sample for that study arm would be people who elected to participate in English, and the other 25% in French. When a study arm was only available in English, 100% of the sample for that study arm would be people who chose to participate in English. Figure 17 shows the flow diagram of randomization.

Allocation

The computer-generated randomization balanced both known and unknown prognostic factors in the assignment of interventions. This was a single-blinded study because I could not mask participants to the fact that they have been randomized to a computer application including a visualization; for example, about measles. However, participants did not know the purpose of the study arm to which they were assigned, and investigators were blinded to the study arm during the data collection and in the pre-preparation of statistical code.

Data collection methods

The trial ran March-July, 2021. After seeking eligible participants' consent, participants were randomized into different arms of the study. Each arm determined which intervention, if any, participants were offered. All participants completed the same post-intervention questionnaire containing questions about risk perception, emotion, knowledge, vaccination intentions and a validated 5C scale about vaccination developed by Betsch and colleagues (2018). I measured COVID-19 vaccination intentions only among people who indicated they had not yet had a COVID-19 vaccine (See Appendix15 for the full questionnaire).

Data management

In order to be considered as contributing valid data, participants randomly allocated to intervention arms were required to spend a predetermined amount of time viewing and/or interacting with the intervention. These time requirements were set based on the minimum time possible for each intervention: control = no restrictions; Herdimm = minimum 206 seconds; Robert Koch = minimum 66 seconds; SBS News = minimum 165 seconds; Guardian = minimum 55 seconds; TheOtherEdmund = minimum 12 seconds; Public Health Agency of Canada = minimum 92 seconds. Participants whose time stamp on the relevant survey page was less than the pre-determined minimum were excluded from the dataset.

All the information I collected was kept confidential and used for research purposes only. In other words, identifying information of participants has not been and will not be associated with the results of the study. No individual information was presented in reports, publications, or presentations. All data has been presented in aggregate form, without individual identifiers. Data was stored on Qualtrics servers located in Canada and subject to Canadian data privacy laws. When I worked with data, the only people who had access to our Qualtrics account were the investigators and our team members who have complete and relevant ethics training. When the data was stored on our computers, each of our computers was protected by a password. The data was stored on a secure server, to which access is maintained and reserved for the members of the team (members of the team affiliated with

Université Laval). After the end of the study, the anonymized data (including non-identifying sociodemographic data and all questionnaire responses) will be deposited in a public repository (Dataverse de l'Université Laval (Université Laval)) which will allow data sharing with the scientific community. No information that would allow anyone to identify a person will be deposited in this public repository. Any other electronic data will be destroyed in June 2027.

Chapter 5: Article 1 - Interventions to help people understand community immunity: A systematic review

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Résumé

Contexte : L'immunité de groupe, ou immunité collective, se produit lorsque les personnes sensibles d'une population sont indirectement protégées contre une infection grâce à l'étenduede l'immunité au sein de la population. Dans cette étude, nous avons cherché à examiner systématiquement les interventions conçues pour communiquer au grand public ce qu'est l'immunité collective et comment elle fonctionne.

Méthodes : Nous avons recherché des articles évalués par des pairs décrivant des interventions avec ou sans évaluation dans PubMed, EMBASE, CINAHL, le Cochrane Central Register of Controlled Trials et Web of Science. Nous avons ensuite effectué des recherches sur le Web avec Google pour identifier les interventions sans publication associée. Nous avons extrait des données sur la population cible des interventions, sur les interventions elles-mêmes (par exemple, si elles décrivaient ce qu'est l'immunité collective et comment elle fonctionne) et sur les effets éventuels des interventions évaluées, puis nous avons fait une synthèse narrative des données. **Résultats :** Nous avons identifié 32 interventions : 11 interventions décrites dans des articles évalués par des pairs et 21 interventions sans article associé. Sur ces 32 interventions, cinq décrivaient ce qu'est l'immunité collective, 6 décrivaient les mécanismes de fonctionnement de l'immunité collective et 21 décrivaient les deux. Des 32 interventions, 14 portaient sur les maladies infectieuses en général, tandis que 13 autres portaient sur une ou plusieurs maladies spécifiques. Douze des 32 interventions utilisaient des vidéos, sept des simulations interactives et six des questionnaires. Des 11 articles évalués par des pairs, dix décrivaient des études évaluant au moins un effet des interventions. Parmi ces dix études, 4/4 ont fait état d'une amélioration des connaissances, 3/5 d'un changement d'attitude en faveur de la vaccination, 2/5 d'une augmentation des intentions de vaccination. Sur trois études évaluant des interventions portant spécifiquement sur l'immunité collective, deux ont signalé une augmentation des intentions de vaccination.

Conclusions : L'un des avantages majeurs de la vaccination se trouve à l'échelle de la population lorsqu'elle atteint l'immunité collective. Il pourrait donc être important d'identifier des moyens de communiquer cet avantage de manière optimale, car certaines données suggèrent qu'une communication efficace à propos de l'immunité collective augmenterais les intentions de vaccination.

Mots clés

Immunité collective ; immunité grégaire ; vaccination ; hésitation à se faire vacciner.

Abstract

Background: Herd immunity, or community immunity, occurs when susceptible people in a population are indirectly protected from infection thanks to the pervasiveness of immunity within the population. In this study, we aimed to systematically review interventions designed to communicate what community immunity is and how community immunity works to members of the general public.

Methods: We searched PubMed, EMBASE, CINAHL, the Cochrane Central Register of Controlled Trials and Web of Science for peer-reviewed articles describing interventions with or without evaluations. We then conducted web searches with Google to identify interventions lacking associated publications. We extracted data about the target population of the interventions, the interventions themselves (e.g., did they describe what community immunity is, and how it works), any effects of evaluated interventions, and synthesized data narratively.

Results: We identified 32 interventions: 11 interventions described in peer-reviewed articles and 21 interventions without associated articles. Of the 32 interventions, 5 described what community immunity is, 6 described the mechanisms of how community immunity occurs and 21 described both. Fourteen of the 32 addressed infectious diseases in general while the other 13 addressed one or more specific diseases. Twelve of the 32 interventions used videos, 7 used interactive simulations and 6 used questionnaires. Ten of the 11 peer-reviewed articles described studies evaluating at least one effect of the interventions. Within these 10, 4/4 reported increased knowledge, 3/5 reported shifts of attitudes in favour of vaccination, 2/5 reported increased intentions to vaccinate. Of 3 studies evaluating interventions specifically about community immunity, 2 reported increased intentions to vaccinate.

Conclusions: A compelling benefit of vaccination exists at the population level in the form of community immunity. Identifying ways to optimally communicate about this benefit may be important, because some evidence suggests that effective communication about community immunity can increase vaccination intentions.

Keywords

Community immunity; Herd immunity; Vaccination; Vaccine hesitancy

Highlights

- Little evidence is available about the effects of communicating about community immunity.
- Effective communication about community immunity may increase vaccine intentions.
- Future research should focus on how to communicate this concept effectively.

Introduction

Many vaccines protect against disease not only by preventing infection in those receiving the vaccine, but also by preventing the infection from being transmitted from one person to another [1,2]. The terms herd immunity and community immunity refer to the indirect protection of unvaccinated people obtained by elevating the pervasiveness of immunity within a population. Such an elevation breaks the chain of transmission and decreases one's probability of contact with an infectious agent [2]. In this paper we use the term community immunity.

Previous research has suggested that potential benefits and harms at the individual level are more influential than those at the community level on people's decisions to immunize or not [3]. However, it is not clear whether community-level benefits are well-understood but simply not important to people, or whether community-level benefits lack influence in individual decisions because such benefits are poorly communicated. That is, are the relationships between individual-level vaccination behaviour and individual- and community-level benefits and harms communicated well to people? If they are communicated well, are people more favourable towards vaccination? Communicating well about community immunity is a complex task, because whether or not a given population achieves community immunity depends on many variables, including vaccine effectiveness, vaccine coverage, distribution patterns of infection among populations, timing of vaccine administration and serotype replacement [4]. Given the underlying complexity of community immunity as a concept, it is plausible that its lack of observed influence on vaccination decisions [5,6] may stem at least partly from a lack of clarity about the concept among members of the public.

In this systematic review, we aimed to synthesize evidence about interventions intended to help members of the general public better understand the concept of community immunity. By interventions, we mean any method, strategy, or tool developed to help people understand the concept of community immunity. Because visualization is a powerful way to convey complex topics [7,8] and because visualizations have proved effective at helping members of the public understand other related mathematical concepts such as how population-based statistics apply to an individual [7,9], we were particularly interested in web-based visualizations as interventions. By visualization, we mean visual presentations of data or information. These presentations may be static or dynamic, and interactive or not. The objective of this systematic review was therefore to describe interventions, including web-based interventions, aimed at conveying the concept of community immunity and to describe any reported effects of such interventions.

Methods

Search strategy

To identify peer-reviewed literature describing interventions designed to communicate the concept of community immunity, we searched PubMed, EMBASE, CINAHL, the Cochrane Central Register of Controlled Trials and Web of Science on April 19, 2016, updated on January 25, 2018 to identify any newer articles. The full search strategy is available in Supplemental file 1 [in thesis: Appendix 1]. We did not apply any language or publication date restrictions. In addition, we retrieved further studies by searching the references of relevant review articles [10–19], by a hand search of articles cited by or cited in the included articles, and by consulting with 33 experts through professional networks of co-authors for suggestions of relevant published or unpublished literature or web based interventions missed during our search.

To identify interventions that may not have associated publications, we conducted an online Google search in two stages. We sought any web-based representations conveying the concept of herd immunity or community immunity. First, on April 24th 2017, we conducted a standard search using Google to find web-based representations which had herd immunity components or were about explaining community immunity. We used six search terms ‘‘Herd immunity”, ‘‘Herd protection”, ‘‘Herd effect”, ‘‘Community protection”, ‘‘Indirect protection”, ‘‘Community immunity” combining each with, ‘‘AND (simulation OR animation OR visualization)”. We reviewed the first 30 results for each search, as it is rare for users to click past the third page of ten search results per page, and therefore, researchers analyzing medical content available on the web often use 30 as a threshold [20–22]. On June 9, 2017, we conducted the same searches in private browsing mode to ascertain whether our results had been affected by a ‘‘filter bubble” [23]; that is, the way Google search results are adapted to one’s previous browsing activity.

Study selection and screening process

Two reviewers (HH, TP) independently identified and screened all studies and web-based interventions for their eligibility. Conflicts were resolved by a third reviewer (HW). We used PICO (Population, Intervention, Comparison, and Outcome) to structure study inclusion and exclusion criteria. Our population of interest was the general public or any subgroup thereof. We sought studies describing any strategies, tools or methods (including campaigns and educational tools) designed to help people understand more about the concept of community immunity. Our comparator was any control, including offering no education about community immunity or comparing participants before and after an intervention. Our outcomes of interest included common outcomes in vaccination acceptance studies: knowledge (comprehension, understanding), attitudes (attitudes toward or against vaccination), beliefs (risk perceptions, perceived benefits), and behavioural intentions (intentions to be vaccinated or not). We also sought to extract any data about emotions (e.g., fear, anxiety), as emotions are key drivers of decisions [24].

We excluded studies that did not have a component specifically about community immunity; for example, studies about policies, policy decision-making, vaccine provision programs, vaccine hesitancy, or anti-vaccine movements. For web-based tools, our inclusion and exclusion criteria used the same specifications regarding population and intervention. We did not apply comparison and outcome criteria to web-based tools because we did not expect these to report evaluation studies. We report this review according to PRISMA guidelines (see PRISMA checklist in Supplemental file 2)[in thesis: Appendix 2]. This systematic review was registered in PROSPERO (CRD42017069206).

Data extraction

Two people (HH, TP) independently extracted data from included articles and web-based interventions. Conflicts were resolved by a third reviewer (HW). From included articles and web-based interventions, we extracted information about: (1) the type of intervention (educational material for home use, live education session, etc.) (2) the medium of the intervention (paper, web, etc.), (3) the objective of the study or intervention, (4) whether the intervention was solely about community immunity or whether it was a broader intervention, (5) whether the intervention aimed to convey the importance or existence of community immunity (the ‘‘what” of community immunity; i.e., the existence of community-level protection to safeguard those who are not immune), how it works (the ‘‘how” of community immunity; i.e., community immunity is achieved by preventing the spread of infection from one person to another within the community), or both. For evaluated interventions, we extracted (6) the characteristics of study participants and (7) outcomes observed.We extracted data about interventions’ effects on knowledge, attitudes, beliefs (perceived benefits, perceived risks), and behaviours. We pre-selected these outcomes based on the Health Belief Model [25,26], a model widely used to predict health related-behaviours and to assess outcomes in studies of interventions about vaccination and immunization [10–13]. People may also rely on emotional, cultural, and social factors before making a decision about vaccination [27,28]. Cultural and social factors are unlikely to be changed by interventions, but emotions may be affected. Therefore, we also extracted data about emotions elicited by interventions based on the Affect Heuristic theoretical framework, which describes the role and importance of emotions in judgment and decisions [24]. Because we sought to understand all possible effects, we did not prespecify any of these as a primary outcome.

Data validation

When we were missing details or were uncertain about data, we contacted authors to review the data we had extracted about their studies. We contacted four authors via email. We received responses from three of these four, who reviewed the draft extractions we had sent as well as provided us with additional data not reported in their publication. After a reminder email with no response, we also followed up with the nonresponding author and their co-authors by email and phone, but were not able to reach any member of the authorship team.

Quality assessment

We used the Mixed Methods Appraisal Tool (MMAT) by Pluye and colleagues [29] to assess the quality of all studies. Quality assessment was conducted independently by two reviewers (HH, TP) and disagreements were settled through discussion until consensus was reached. Remaining conflicts among them were resolved by a third reviewer (HW).

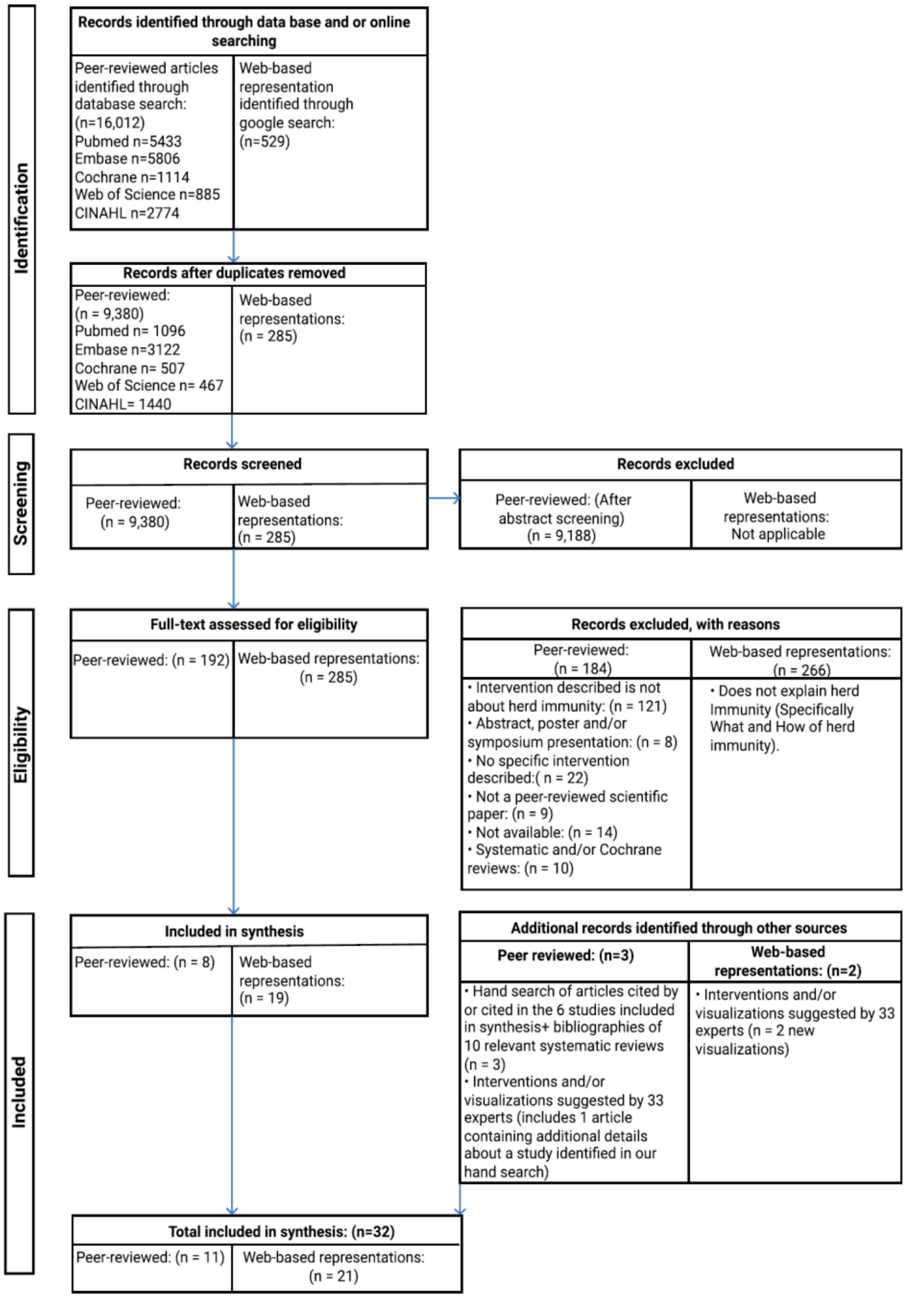
Data synthesis

We organized data in tables and synthesized it descriptively. We also calculated observed heterogeneity (Higgins I^2) to determine whether it would be possible to conduct meta-analyses of available randomized controlled trials [30,31] on common outcomes, namely, behavioural intentions, perceived risk of disease, and perceived risks of vaccination. We used package meta version 4.4.0 [32] within R version 3.3.0 [33] for these calculations.

Results

Articles identified, scope of literature

We identified a total of 16,012 records through database searches and 529 interventions through Google searches. After removing duplicates, we screened 9,380 database records and 285 Web-based representations. After our private browsing mode search, no change was detected that was different from our previous search. Through these methods, we identified 8 articles and 19 web-based representations. Hand-searching yielded three other articles and two additional web-based representations. Thus, our final data set included 11 peer-reviewed articles and 21 web-based representations, for a total of 32 interventions. Fig. 1 below shows our PRISMA diagram.



Out of 11 interventions described in peer-reviewed articles, 3 were solely about community immunity while the other 8 had a component about community immunity within a larger intervention (Table 1)[in thesis: Table 11]. Out of 21 web-based representations, 18 were solely about community immunity while the other 3 had a component about community immunity within a larger intervention (Table 2) [in thesis: Table 12]. Thus, out of 32 interventions in total (peer-reviewed and web-based representations together), 21 were solely about community immunity, and 11 had included community immunity as a component of a larger intervention. Five interventions aimed to convey the ‘‘what” of community immunity, meaning what it is, six addressed the ‘‘how” of community immunity, meaning how it works, and 21 interventions addressed both (Table 3) [in thesis: Table 13]. As shown in Table 3 [in thesis: Table 13], web-based representations generally included elements of the ‘‘how” of community immunity whereas this was not necessarily the case for interventions presented in the peer-reviewed literature. For example, 4 out of 11 (36%) interventions described in the peer-reviewed literature conveyed that community immunity works by preventing the spread of infection, whereas 17 out of 21 (81%) web-based representations did the same. Ten out of 11 peer-reviewed articles reported evaluating the intervention according to at least one of our outcomes of interest and described the demographic characteristics of participants (Table 4; Table 5) [in thesis: Table 14; Table 15].

Quality assessment

Table 4 [in thesis: Table 14] provides Mixed Methods Assessment Tool scores of all evaluated peer-reviewed articles included in our review. Of the ten studies, four had high quality scores (75% or above), two were of medium quality (50%) and four were of low quality (25%) on this measure. Supplemental files 3 and 4 [in thesis: Appendix 16 and 17] provide full details.

Effects of evaluated interventions

Ten studies evaluated at least one of our outcomes of interest. Summarized outcomes are shown in Tables 5 and 6 [in thesis: Table 15; Table 16].

Effects on knowledge

Four studies that assessed knowledge (2 high quality, 1 medium quality, 1 low quality) showed an increase in knowledge about immunization in general [34–37]. These studies were larger interventions that included information about community immunity as a component of the intervention. The community immunity component was not evaluated independently.

Effects on attitudes

Three studies out of five that assessed attitudes (1 high quality, 1 medium quality, 3 low quality) showed the intervention may have shifted attitudes more in favour of vaccination [35–39]. These studies were also larger interventions that included information about community immunity as a component of the intervention.

Effects on intentions to vaccinate

Two of the five studies that assessed intentions to vaccinate (3 high quality, 1 medium quality, 1 low quality) showed increased intentions to vaccinate. One of these two studies (high-quality) was of an intervention specifically about community immunity showed an increase in intentions to vaccinate when the intervention was interactive and the concept of community immunity was explained [31]. The other of the two studies (low quality) showed that the intervention may increase interest in vaccination if the concept of community immunity was explained as one's vaccination protecting others in society [40].

Effects on emotions

No studies evaluated the effects of interventions on emotions.

Effects of interventions solely about community immunity

Out of the three studies that evaluated the effects of an intervention solely about community immunity, all three assessed intentions to vaccinate as their sole outcome. Two of the three resulted in an increase in intentions to vaccinate [31,40] while the other demonstrated no change [30].

Meta-analysis

Two randomized controlled trials [30,31] tested outcomes in common, specifically, the effects of communicating information about community immunity on behavioural intentions, perceived risk of disease, and perceived risk of vaccination. Mean I^2 estimates were 63% (see Supplemental file 5)[in thesis: Appendix 18]. This high heterogeneity between the two studies meant that reliable meta-analytic results were not possible.

Discussion

In this study, we aimed to describe interventions aimed at conveying the concept of community immunity and to describe any reported effects of such interventions. Our results lead us to four principal findings.

First, there is relatively little evidence about the effects of communicating about community immunity. Although a number of interventions described in the literature included a component about community immunity, few studies isolated the effects of such a component. This makes it difficult to interpret and report the effectiveness of interventions about community immunity, as any effects of these larger interventions may be due to their other components. However, within the limited sample of interventions specifically about community immunity, we observed that two out of three such interventions resulted in increases in intentions to vaccinate [31,40]. This suggests that communicating population-level benefits of vaccination may encourage vaccine uptake.

Second, we identified a number of interventions available online for which we were unable to find associated evaluation studies. These web-based representations often showed people not only what community immunity is, but also how it is achieved.This may be easier to do using dynamic methods such as visualization. It is unknown, however, whether such demonstrations make a difference, meaning that although communicating about community immunity may encourage vaccination, there remains little evidence about how to do this most effectively. Future research could compare different ways of communicating about community immunity to assess their influence on people's views about their role in protecting their community from infectious disease.

Third, studies in this review offered few results regarding variables that shape vaccination intentions, such as knowledge or emotion. Although several studies reported effects on knowledge about immunization, few reported knowledge specifically about community immunity and none assessed emotions as outcomes. Emotions are critical to human decision-making [41] and influence decisions through their effects on risk perception [47], attitudes, and behavioural intentions [42–44]. Future research about the effects of communication interventions might therefore be improved by evaluating interventions' effects on emotions in addition to knowledge, attitudes, beliefs, and behavioural intentions.

Fourth and finally, our review documented that most included interventions were designed for high-income, Western countries. Moreover, evaluation studies measured the effects of their intervention mostly on sub-populations of school, college or university students. These population selection factors raise questions about the potential differential effects of interventions among members of the general population with varied age groups or education levels. One intervention that was designed to be used across cultures was more effective in encouraging vaccination intentions in Western countries than it was in Eastern countries. The authors noted that this was possibly because baseline vaccine uptake was already high in Eastern countries and there was therefore less room for change [31]. Cultural differences and differences between countries in terms of vaccination programs may be important to consider when analyzing public responses to interventions.

To the best of our knowledge, there are no previous systematic reviews synthesizing interventions to convey the concept of community immunity. Previous work has been mostly focused on improving knowledge, attitudes, beliefs, and behavioural intentions in order to improve immunization or vaccination coverage, with limited research on how and whether the concept of community immunity might be conveyed.

Our systematic review had two main limitations. First, we may be missing relevant data. Although we aimed to be meticulous in our search strategy, it is possible that we missed some relevant studies or interventions. Even among included studies, when publications lacked details, some authors responded to our queries while others were not reachable. In addition, although we did not apply any language restriction when searching databases, our missed interventions in other languages. Second, most of our evaluation data came from studies of interventions that included information about community immunity as a component of an overall intervention. This means that, in most cases, we were unable to isolate the effects of community immunity components.

Conclusions

This systematic review demonstrates that despite the existence of a number of interventions available for conveying the concept of community immunity, little is known about how to make this concept comprehensible to members of the general population. Identifying ways to do this may be important, because some evidence suggests that effective communication about community immunity can increase vaccine intentions. Future research should focus on how to communicate this concept effectively and should evaluate interventions' effects on vaccine intentions and uptake as well as their precursors, such as knowledge, attitudes, beliefs and emotions.

Authors' contributions

HH, HW contributed to the design of the study. HH, TP and HW contributed to data collection. HH and HW conducted data analysis and interpretation. HH and HW drafted the first version of the article with early revision by HH, TP and HW. HH, TP, CTC, ED, TG, AMCG, NMI, SMD, JSP, KW, DR, HW critically revised the article and approved the final version for submission for publication. HH, TP and HW had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Conflict of interest

None.

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Table 11: Peer-reviewed literature regarding interventions about community immunity

Reference	Type of intervention	Medium of intervention	Objective of study/paper	Is intervention solely about community immunity?	Was the intervention evaluated?	Disease(s) used to explain community immunity
Anderson, 2015[45]	Questionnaire	Online	To increase the knowledge, skills, and attitudes of nurse practitioners and assist them in their understanding of immunizations and its impact on humans.	No	No	Not Reported
Awadh et al., 2014[34]	Educational animated 10-min video + Didactic 50-min PowerPoint lecture	Online + Verbal	To assess short educational intervention for improving parents' knowledge about childhood vaccination.	No	Yes	Not Reported
Betsch et al., 2013[30]	Questionnaire	Online	To assess the consequences of communicating the social and/or individual benefits of herd immunity on vaccination	Yes	Yes	Fictitious disease

			intentions and uptake.			
Betsch et al.,2017; Brockmann 2017; Dirk Brockmann 2017 [31,46,47]	Interactive simulation + Text-based	Online	To assess the influence of communicating the mechanism of herd immunity on vaccination intentions.	Yes	Yes	Not Reported
Carolan et al., 2018 [38]	PowerPoint presentation + Interactive simulation	Online	To assess the effects of an interactive simulation and traditional educational interventions on young adults' attitudes towards vaccination and level of confidence in knowledge of vaccination.	No	Yes	Measles, Mumps, Smallpox or Influenza
Gargano et al., 2014 [35]	Brochure (for parents)/ PowerPoint presentation + Videos (for adolescents)	Paper + Online + Verbal	To describe the development, theoretical framework and evaluation of an intervention designed to enhance adolescent	No	Yes	Influenza, Diphtheria, Tetanus, Pertussis, Meningococcal disease and Human papillomavirus

			vaccination rates and to promote adolescent vaccine acceptance among parents and adolescents attending middle and high schools.			
Glik et al., 2004 [36]	10-15-min motivational video and 5-module curriculum (1 describing herd immunity).	Online + Paper	To increase awareness, improve attitudes, and facilitate proactive behaviour about immunization by implementing an immunization promotion curriculum (Immunization Plus) for young adolescents, their parents, and teachers.	No	Yes	Not Reported
Hendrix et al., 2014 [48]	Questionnaire	Online	To determine whether emphasizing the benefits of measles-mumps-rubella (MMR) vaccination directly to the	No	Yes	Measles, Mumps and Rubella

			vaccine recipient or to society differentially impacts parents' vaccine intentions for their infants.			
Kennedy et al., 2008[39]	Questionnaire	Paper	To obtain suggestions for the optimal presentation of vaccine-related information and to determine if an educational intervention influences mothers' vaccine safety attitudes.	No	Yes	Measles, Mumps and Rubella
Melton et al., 2013; Schoeppe et al., 2017 [37,49]	Training; Technical Assistance; Communications; Support (via Posters, Flyers, 5 reasons card, Images and videos, Parent Action Guide (a resource for PAs), postcards, stickers, and branded giveaway items	Verbal + Paper + Online	To address parental vaccine hesitancy by empowering parents to be immunization advocates, improving awareness of immunization as a social norm among parents at participating sites, and changing those	No	Yes	Not Reported

	(e.g., first aid kits, notebooks); Questionnaire		parents' attitudes and behaviours.			
Vietri et al., 2012 [40]	Questionnaire (in which scenarios are embedded)	Online	To evaluate the circumstances under which vaccination decisions are influenced by a potential benefit for others (altruism) and examine the conditions under which potential benefit for others operates.	Yes	Yes	Human Papillomavirus and Influenza

Table 12: Web-based visualizations regarding interventions about community immunity

Reference	URL	Country	Type of intervention	Medium of intervention	Is intervention solely about community immunity?	Disease(s) used to explain community immunity
Amanda Martyn, 2016 (North Carolina School of Science and Mathematics)	https://www.ncssm.edu/learning-innovations/2016/10/27/ncssm-instructor-s-animation-stresses-the-importance-of-vaccination-and-herd-immunity	United States	Video	Online	Yes	No specific disease
Carolyn Kylstra, 2015 (Buzzfeed News)	https://www.buzzfeed.com/carolynkylstra/vaccines-and-herd-immunity?utm_term=.drmPwQzxo0#.pl8e0YMaKx	United States	GIF	Online	Yes	Measles and Ebola.
College of Physicians of Philadelphia	https://www.historyofvaccines.org/content/herd-immunity-0	United States	Video	Online	Yes	No specific disease
Emily Willingham and Laura Helft, 2014	http://www.pbs.org/wgbh/nova/body	United States	Static Image	Online	Yes	Measles, Chicken pox and Polio

	/herd-immunity.html					
ExSciEd, 2013	https://www.youtube.com/watch?v=CPcC4oGB_o8	Unknown	Video	Online	Yes	Diphtheria, Tetanus, Mumps, Polio, Measles and Smallpox
Guardian US interactive team, 2015	http://www.theguardian.com/society/ng-interactive/2015/feb/05/-sp-watch-how-measles-outbreak-spreads-when-kids-get-vaccinated	United Kingdom (US branch)	Simulation	Online	No	Measles
Harvard Health Publication	http://www.health.harvard.edu/herd-immunity-animation	United States	Video	Online	Yes	No specific disease
Liz Ruttenbur, 2014	http://www.wsusignpost.com/2014/11/13/herd-immunity/	United States	Static Image	Online	Yes	No specific disease
[Name not given]	http://op12no2.me/toys/herd/	Unknown	Interactive simulation	Online	Yes	No specific disease
Never Stop Dreaming, 2016	https://www.youtube.com/watch?v=6waMp4GgvcA	Unknown	Video	Online	Yes	No specific disease

NHS Public Health England, 2015	http://www.nhs.uk/Video/Pages/Vaccinationanimation2.aspx	England	Video	Online	Yes	No specific disease
NRVS, 2016	http://nrvs.info/faqs/herd-immunity-or-community-immunity/	Australia	Graphics	Online	Yes	No specific disease
Romina Libster, 2015 (Ted Talk)	https://www.ted.com/speakers/romina_libster	Argentina	Talk	Online	Yes	Measles
Salathé Group 2014	http://vax.herokuapp.com/herdImmunity	Switzerland	Interactive game	Online	Yes	Measles
Sarah Stapleton, 2015	https://www.vinceandassociates.com/blog/herd-immunity-explained-by-gif/	United States	Blog (with GIFs)	Online	Yes	Measles
Shane Killian, 2010	http://www.software3d.com/Home/Vax/Immunity.php	Unknown	Interactive simulation	Online	Yes	No specific disease
Techydad, 2010	http://www.techydad.com/Vaccinate/	Unknown	Interactive simulation	Online	No	No specific disease

Theotheredmund, 2016	https://www.reddit.com/r/dataisbeautiful/comments/5v72fw/how_herd_immunity_works_oc/	Unknown	Simulation	Online	Yes	No specific disease
Thomas Lumley, 2014	(https://www.youtube.com/watch?v=KkMD6KGgltU; https://www.youtube.com/watch?v=uw93SdC-ouo; https://www.youtube.com/watch?v=ivRBM03gPwM; https://www.youtube.com/watch?v=xTmHUegqcrA)	Unknown	Video	Online	Yes	No specific disease
University of Pittsburgh, 2015	http://fred.publichealth.pitt.edu/measles/	United States	Interactive simulation	Online	No	Measles
Vaccines Today, 2015	https://www.vaccinestoday.eu/stories/what-is-herd-immunity/	Europe	Video	Online	Yes	No specific disease

Table 13: The importance and mechanisms of community immunity in the interventions

References	"What?" Were they seeking to convey the importance/existence of community immunity (e.g., community immunity protects those who aren't or can't be vaccinated)? If yes, what was the message?		"How?" Were they seeking to convey how community immunity works; i.e., the mechanism of community immunity (e.g., community immunity works by preventing the spread of infection such that those who aren't or can't be vaccinated are less likely to encounter the infection)? If yes, what was the message?		
	Community immunity protects others who are not immune	**Community immunity protects people who are vulnerable (old, young, sick, immunocompromised)**	**Community immunity provides protection by reducing/stopping the spread of infection**	**Community immunity provides protection when enough people are immune/get vaccinated**	**Community immunity provides protection when enough people are immune/get vaccinated varies by disease**
Peer-reviewed literature					
Anderson, 2015 [45]	Conveyed	Not conveyed	Conveyed	Conveyed	Not conveyed
Awadh et al., 2014 [34]	Conveyed	Not conveyed	Not conveyed	Not conveyed	Not conveyed
Betsch et al., 2013 [30]	Conveyed	Conveyed	Conveyed	Conveyed	Not conveyed

Betsch et al., 2017; Brockmann, 2017; Dirk Brockmann, 2017 [31,46,47]	Conveyed	Conveyed	Conveyed	Conveyed	Conveyed
Carolan et al., 2018 [38]	Conveyed	Conveyed	Not conveyed	Conveyed	Conveyed
Gargano et al., 2014 [35]	Conveyed	Conveyed	Conveyed	Conveyed	Not conveyed
Glik et al., 2004 [36]	Conveyed	Not conveyed	Not conveyed	Not conveyed	Not conveyed
Hendrix et al., 2014 [48]	Conveyed	Conveyed	Not conveyed	Not conveyed	Not conveyed
Kennedy et al., 2008[39]	Not conveyed	Not conveyed	Not conveyed	Conveyed	Conveyed
Melton et al., 2013; Schoeppe et al., 2017 [37,49]	Conveyed	Not conveyed	Not conveyed	Not conveyed	Not conveyed
Vietri et al., 2012 [40]	Not conveyed	Not conveyed	Not conveyed	Conveyed	Conveyed
Web-based representations					

Amanda Martyn, 2016 (North Carolina School of Science and Mathematics) [50]	Conveyed	Conveyed	Not conveyed	Not conveyed	Not conveyed
Carolyn Kylstra, 2015 (Buzzfeed News) [51]	Conveyed	Conveyed	Conveyed	Conveyed	Conveyed
College of Physicians of Philadelphia [52]	Conveyed	Conveyed	Conveyed	Conveyed	Not conveyed
Emily Willingham and Laura Helft, 2014 [53]	Conveyed	Conveyed	Conveyed	Conveyed	Not conveyed
ExSciEd, 2013 [54]	Conveyed	Not conveyed	Conveyed	Conveyed	Not conveyed
Guardian US interactive team [55]	Conveyed	Not conveyed	Not conveyed	Conveyed	Conveyed
Harvard Health Publication [56]	Conveyed	Not conveyed	Not conveyed	Conveyed	Not conveyed
Liz Ruttenbur, 2014 [57]	Conveyed	Not conveyed	Conveyed	Conveyed	Not conveyed

Never Stop Dreaming, 2016 [58]	Conveyed	Not conveyed	Conveyed	Conveyed	Conveyed
NHS Public Health England 2015 [59]	Conveyed	Not conveyed	Conveyed	Conveyed	Not conveyed
[Name not given] [60]	Conveyed	Conveyed	Conveyed	Conveyed	Not conveyed
NRVS, 2016 [61]	Conveyed	Conveyed	Conveyed	Conveyed	Not conveyed
Romina Libster Ted Talk 2015 [62]	Conveyed	Not conveyed	Conveyed	Conveyed	Conveyed
Salathé Group 2014 [63]	Conveyed	Conveyed	Conveyed	Conveyed	Conveyed
Sarah Stapleton, 2015 [64]	Conveyed	Conveyed	Conveyed	Conveyed	Conveyed
Shane Killian, 2010 [65]	Not conveyed	Not conveyed	Conveyed	Conveyed	Not conveyed
Techydad, 2010 [66]	Not conveyed	Not conveyed	Conveyed	Conveyed	Not conveyed
Theotheredmund, 2016 [67]	Conveyed	Conveyed	Conveyed	Conveyed	Not conveyed
Thomas Lumley, 2014 [68]	Not conveyed	Not conveyed	Conveyed	Conveyed	Not conveyed

University of Pittsburgh, 2015 [69]	Not conveyed	Not conveyed	Not conveyed	Conveyed	Conveyed
VaccinesToday, 2015 [70]	Conveyed	Conveyed	Conveyed	Conveyed	Conveyed

Table 14: Characteristics of participants and quality score of peer-reviewed literature describing the interventions

Reference	Country	Sample size (n)	Study population/ intended audience	Age	Sex/Gender (n, percentage)	Ethnicity (n, percentage)	Socioeconomic variables	*MMAT Quality score (percentage)
Anderson, 2015 [45]	United States	Not applicable (intervention not evaluated)	Nurse practitioners	Not applicable (intervention not evaluated)	Not applicable (intervention not evaluated)	Not applicable (intervention not evaluated)	Not applicable (intervention not evaluated)	Not applicable (intervention not evaluated)
Awadh et al., 2014 [34]	Malaysia (Kuantan)	n=73	Parents	30 and 40 years	Women (n=64, 88%); Men (n=9, 12%)	Malay (n=66, 90%); Chinese (n=7,10%)	Employed (n=59/73); Unemployed (n=14/73)	75%
Betsch et al., 2013[30]	Not reported	n=342	Students and non-students	Mean age 30 years (*SD 13)	Female (n=221, 64%)	Not reported	Abitur (German University entrance diploma) or higher level of education (n = 301, 88%)	50%

Betsch et al., 2017; Brockmann, 2017; Dirk Brockmann; 2017 [31,46,47]	South Korea, Vietnam, Hong Kong, United States, Germany and the Netherlands	n=2107 participants	General population	Mean age 29 years (SD 10)	1217 respondents were women (58%). 890 respondents were male (42%).	Not reported	85% of the sample had a high school diploma or a higher level of education.	100%
Carolan et al., 2018 [38]	England	n=63	Students	Age ranging from 14-18 years	Male (n=34, 54%); Female (n=29, 46%)	Asian/Asian British (n=3, 4.76%); Mixed Ethnic Background (n=1,1.59%); White British (n=59,94%)	Not Reported	25%
Gargano et al., 2014 [35]	United States (Georgia)	n=184 (parents); n=667 (middle-school students); n=401 (high-school students)	Parents/Adolescents	Not Reported	Not Reported	Not Reported	Not Reported	25%

Glik et al., 2004 [36]	United States (California counties)	n=929	Students (6th to 8th grade)	Age ranging from 10-12 years	Equal numbers of boys and girls	Hispanic (n=460, 50%); Mixed Hispanic and another Race (n=16, 2%); White (n=185, 20%); White and other (n=20, 2%); Black (n=131, 14%); Asian Americans (n=94, 10%); Native Americans (n=20, 2%)	Not Reported	75%

Hendrix et al., 2014 [48]	United States (Indiana)	n=802	Parents	Mean age 29 years (SD 7)	Male (n=172, 21.6%); Female (n=626, 78.5%)	Hispanic/ Latino (n=125, 15.7%; Not Hispanic/Latino (n=673, 84.3%	Household income (<10 000= n= 90, 11.4%; $10,000-$24,999=n= 135,17.1%; $25,000-$49,999=n= 248, 31.4%; $50,000-$75,000=n= 181, 22.9%; >$75,000= n=136, 17.2%)	75%

Kennedy et al., 2008 [39]	United States cities	n=927	Mothers; Scientists; Women with no children	25–34 (n=496, 54%); 35–45 (n=431, 47%)	Female	non-Hispanic white mothers (n=927, 100%)	Employment status: Employed (n=873, 94%); Not employed (n=54, 6%); Education: Less than a high school graduate (n=27, 3%); High school graduate (n=160, 17%); Some college (n=373, 40%); College graduate (n=266, 29%); Post graduate degree (n=98, 11%)	25%
Melton et al., 2013; Schoeppe et al., 2017 [37,49]	United States (Washington State)	Pre-test n=460; Post-test n=238	Parents	Not Reported	Not Reported	Not Reported	Not Reported	50%

Vietri et al., 2012 [40]	Not Reported	n=292 (1st study); n=291 (2nd study); n=299 (3rd study)	College students	Not Reported	**Study 1.** Female (n=124, 43%); Male (n=168, 58%) **Study 2 and Study 3**=Not Reported	Not Reported	Not Reported	25%

*MMAT= Mixed method assessment tool; *SD = Sample standard deviation; Inter rater reliability = 83%

Table 15: Summaries of evaluation studies

Article(s)	Study Design and comparison type(s)	Comparison and sample size (n)	Summary of findings relevant to cognition (includes knowledge, comprehension, understanding, etc.), attitudes (includes attitudes toward or against vaccination, etc.), behavioural intentions (includes getting vaccinated or not, etc.) and emotions (fear, anxiety, etc.).
Awadh et al., 2014 [34]	Cross-sectional study using pre- and post-test intervention survey of a single group.	Compared difference in knowledge before and after intervention. (n=73)	Parents' knowledge improved by 2.31 points on 10-point scale ($p<0.001$). Pre-intervention mean knowledge score was 6.84 (*SD 1.52); post-intervention mean knowledge score was 9.15 (SD 0.79).

Betsch et al., 2013 [30] *(community immunity component evaluated independently)*	Online randomized controlled trial using a factorial 2x2x2 between-subjects experimental design with individual benefit of herd immunity (communicated versus. not communicated), social benefit of herd immunity (communicated versus. not communicated), and costs of vaccination (low versus. high) as factors. A control group received no information about herd immunity.	Vaccination intentions were assessed when communicating or not communicating the social benefits of herd immunity. (n=342)	Communicating the social benefits of vaccination did not influence vaccination intentions. Mean intentions to vaccinate on a scale from 1 = 'definitely not vaccinate' to 7 = 'definitely vaccinate' were 3.89 in the control group (SD 1.78) and 4.01 in the group receiving information about social benefits of vaccination (SD 1.86).

Betsch et al., 2017; Brockmann, 2017; Dirk Brockmann; 2017 [31,46,47] *(community immunity component evaluated independently)*	Online randomized controlled trial using a factorial experimental design with both within- and between-subject factors. Specifically, the experiment used a 2 (cultural background: collectivistic Eastern countries versus individualistic Western countries; quasi-experimen-tal between subjects) × 3 (communication format: interactive simu-lation versus text-based explanation versus no explanation of herd immunity; between subjects) × 2 (individual versus social benefit of herd immunity; between subjects) × 2 (basic reproduction number of the disease determining the contagiousness, R0: 3 versus 15; within subjects with counterbalanced order of appearance) × 2 (vaccination uptake: 42% versus 62%; randomly selected for each scenario) mixed design. The control group received no information.	Vaccination intentions were assessed when information was communicated through interactive simulation versus text-based explanation. Vaccination intentions were assessed when the mechanism of herd immunity was explained versus when no information about herd immunity was provided. Vaccination intentions were assessed among Eastern and Western countries when herd immunity mechanism was explained versus no information. (n=2,107)	Mean increases in intentions to vaccinate on a 101-point scale were 8.71 (SD 28.91) in the group receiving an interactive simulation to explain herd immunity and 4.05 (SD 29.55) in the group receiving text to explain herd immunity. Mean increases in intentions to vaccinate on a 101-point scale were 58.64 (SD 29.37) in conditions when herd immunity was explained and 52.95 (SD 29.16) receiving no information. Mean increases in intentions to vaccinate on a 101-point scale were 11.27 (SD 31.45) among Western countries when herd immunity was explained relative to no information and 1.18 (SD 26.03) among Eastern countries.

Carolan et al., 2018 [38]	Randomized controlled trial (three parallel arms): (a) presentation-based intervention, (b) interactive simulation-based intervention; and (c) control arm (no intervention)	Attitudes towards vaccination were assessed among students. (n=63)	No statistically significant differences were found between the three groups immediately after the intervention, nor after six months.
Gargano et al., 2014 [35]	Randomized controlled trial (three parallel arms): (a) an educational brochure targeted to parents, (b) the parent brochure and a science teacher–delivered intervention targeted to students; and (c) a control arm (no intervention).	Vaccine related knowledge was assessed among students. Attitudes towards vaccines and vaccination were assessed (influenza vaccines) among students.(n=667 middle-school students; n=401 high-school students)	There was an increase in knowledge about vaccines and how they work. A statistically significant increase in knowledge among students of middle and high school for the item about herd immunity "By getting a vaccination, you protect others as well as yourself". The intervention may have shifted attitudes towards seeing flu as serious disease and vaccines providing protection; however, there was no adjustment for multiple hypothesis tests.

Glik et al., 2004 [36]	Quasi-experimental non-equivalent comparison-groups waiting list design (4 parallel arms): (a) training of teachers in the curriculum followed by curriculum implementation; (b) curriculum implementation, without teacher training; (c) screening of the *Immunization Day* video as the only intervention; and (d) no intervention.	Knowledge, attitudes towards immunization and health related behaviours were assessed. (n=929)	The intervention (curriculum) increased knowledge about immunization and health related behaviours and shifted attitudes more in favor of vaccination. It did not improve vaccination intention nor vaccination status.

Hendrix et al., 2014 [48]	Randomized controlled trial (4 parallel arms) of vaccine messages (a) the MMR (Measles Mumps and Rubella) Vaccine Information Statement (VIS), which is standard information from the CDC describing MMR and the MMR vaccine; (b) VIS plus additional information highlighting the MMR vaccine's benefits directly to the child receiving the vaccine; (c) VIS plus additional information highlighting the MMR vaccine's benefits to society at large; and (d) VIS plus additional information highlighting the MMR vaccine's benefits directly to the child receiving the vaccine and to society at large.	Vaccine- related intentions were assessed by questionnaire among parents (1-item questionnaire: "On the scale below, please indicate how likely you are to have your baby receive the MMR vaccine." 11-point response scale ranged from 0 not at all likely, to 100 extremely likely, in increments of 10) (n=802)	Information emphasizing the MMR vaccine's benefits to society did not significantly change intentions to vaccinate one's child.

Kennedy et al., 2008 [39]	Randomized controlled trial (5 parallel arms): (a) ‘‘risk comparison’’ message, vaccination information statement (VIS), (b) ‘‘reduced coverage’’ message VIS, (c) ‘‘both messages’’ VIS, (d) standard VIS (‘‘control group’’), or (e) no test materials (‘‘surveys only’’ group).	Vaccine-related attitudes were assessed pre- and post-intervention by a questionnaire (one item, 5-point Likert scale) related to herd immunity: “It is important to vaccinate my child in order to prevent the spread of disease in my community.” (n=927)	No significant changes in vaccine-related attitudes.
Melton et al., 2013; Schoeppe et al., 2017 [37,49]	Unmatched cross-sectional web-based surveys before and after implementation of intervention.	Parents’ vaccine knowledge, attitudes and beliefs were assessed. Knowledge was defined as selecting the correct multiple choice answer to the question, “What percentage of people in your community need to be vaccinated for everyone to be protected from disease?” with the correct answer, “almost all (95% to 100%)”. Attitudes and beliefs were measured using responses on a Likert scale to 13 statements. (Pre-test n=460; Post-test n=238)	75.9% of parents selected the correct response pre-intervention and 78.4% of parents selected the correct response post-intervention (non-significant). Four out of 13 items describing statements of attitudes and beliefs showed statistically significant differences; however, no adjustments were made to account for multiple hypothesis testing.

Vietri et al., 2012 [40] *(community immunity component evaluated independently)*	Three cross-sectional studies	Likelihood to get vaccinated was assessed for different vaccines under different conditions (e.g., percentage of others immune, percentage of others vulnerable) using an 11-point scale of intervals of 10% ranging from 0% to 100%. (Study 1 n=292; Study 2 n=291; Study 3 n=299)	In two of the three studies, likelihood of being vaccinated was sensitive to how many others could potentially be helped by one's own vaccination. In Study 2, mean likelihood of getting vaccinated when there would be no benefit to oneself was 81% (SD 30%) when 95% of the population would benefit compared to 74% (SD 27%) when 10% of the population would benefit ($p<.001$, eta-squared=0.10). Study 3 replicated the finding that people indicate willingness to be vaccinated purely to help others (means not reported).

Table 16: Summary of effects in evaluation studies

Article(s)	Knowledge	Attitudes	Intentions	Emotions
Awadh et al., 2014 [34]	**measured: increased**	not measured	not measured	not measured
Betsch et al., 2013 [30] *(community immunity component evaluated independently)*	not measured	not measured	**measured: no change**	not measured
Betsch et al., 2017; Brockmann, 2017; Dirk Brockmann; 2017 [31,46,47] *(community immunity component evaluated independently)*	not measured	not measured	**measured: increased**	not measured
Carolan et al., 2018 [38]	not measured	**measured: no change**	not measured	not measured
Gargano et al., 2014 [35]	**measured: increased**	**measured: may have shifted towards seeing flu as a serious disease and vaccines providing protection, but no adjustments for multiple hypothesis testing**	not measured	not measured

Glik et al., 2004 [36]	**measured: increased**	**measured: shifted more in favour of vaccination**	**measured: no change**	not measured
Hendrix et al., 2014 [48]	not measured	not measured	**measured: no change**	not measured
Kennedy et al., 2008 [39]	not measured	**measured: no change**	not measured	not measured
Melton et al., 2013; Schoeppe et al., 2017 [37,49]	**measured: small increase (2.5 percentage points) in people selecting correct answer but no statistical test of significance**	**measured: some items changed but no adjustments for multiple hypothesis testing**	not measured	not measured
Vietri et al., 2012 [40] *(community immunity component evaluated independently)*	not measured	not measured	**measured: sensitive to how many people would be helped**	not measured

Chapter 6: Article 2 - A Web Application About Herd Immunity Using Personalized Avatars: Development Study

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Résumé

Contexte: L'immunité de groupe, ou immunité collective, désigne la réduction du risque d'infection chez les individus vulnérables d'une population par la présence et la proximité d'individus immunisés. Des études récentes suggèrent qu'une meilleure compréhension de l'immunité collective pourrait faire augmenter l'intention de se faire vacciner.

Objectif: Cette étude vise à concevoir une application Web à propos de l'immunité collective et à optimiser cette application en fonction des réponses cognitives et émotionnelles des utilisateurs.

Méthodes: Notre équipe multidisciplinaire a développé une application Web à propos de l'immunité collective pour communiquer des données épidémiologiques probantes de manière personnalisée. Dans notre application, les utilisateurs sont invités à construire leur communauté en créant un personnage qui les représente (leur avatar) et huit autres personnages qui représentent des personnes de leur entourage, par exemple leur famille ou leurs collègues de travail. L'application intègre ces avatars dans une animation de deux minutes montrant comment différents paramètres (par exemple, la couverture vaccinale et les contacts au sein des communautés) influencent l'immunité collective. Nous avons prédéfini des objectifs de communication, créé des prototypes et itérativement testé quatre versions de notre visualisation, d'une part dans un laboratoire universitaire d'interaction humain-machine et d'autre part dans des lieux publics (une cafétéria, deux centres commerciaux et une bibliothèque publique). Les données comprenaient des mesures psychophysiologiques (oculométrie, conductance cutanée, reconnaissance des émotions faciales et électroencéphalographie) visant à évaluer les réponses cognitives et affectives des participants. Les données comprenaient également des commentaires verbaux pour évaluer l' interprétation du contenu et du message de la visualisation.

Résultats: Sur les 110 participants des quatre cycles, 68 (61,8 %) étaient des femmes et 38 (34,5 %) des hommes (4/110, 3,6 % ; non communiqué), avec un âge moyen de 38 (écart-type 17) ans. Plus de la moitié (65/110, 59,0 %) des participants ont déclaré avoir une formation de niveau universitaire. Les changements apportés itérativement au cours des cycles comprenaient : l'ajout de la possibilité pour les utilisateurs de créer leurs propres avatars, l'ajout de des symboles spécifiques concernant l'identité des personnes représentées

par les différents personnagesla mise en place, l’'utilisation de la couleur et du mouvement pour indiquer la protection ou l'absence de protection contre les maladies infectieuses, ainsi que des modifications à la terminologie pour adapter le texte aux personnes ayant des différents niveaux d'éducation. Dans l'ensemble, nous avons observé trois résultats généralisables. Premièrement, la visualisation semble effectivement être un moyen prometteur de faire comprendre ce qu'est l'immunité collective et comment elle fonctionne. Deuxièmement, en impliquant plusieurs utilisateurs dans un processus de conception itératif, il est possible de créer une visualisation courte et simple qui transmet clairement un sujet complexe. Enfin, l'évaluation des réponses émotionnelles des utilisateurs au cours du processus de conception, en plus de leurs réponses cognitives, permet de mieux comprendre la conception finale d'une intervention.

Conclusions: La visualisation avec des avatars personnalisés peut aider les gens à comprendre leur rôle individuel dans la santé de la population. Notre application s'est révélée prometteuse en tant que méthode de communication de la relation entre le comportement individuel et la santé de la communauté. Les prochaines étapes consisteront à évaluer les effets de l'application sur la perception des risques, les connaissances et les intentions de vaccination dans le cadre d'un essai contrôlé randomisé. Cette étude offre une stratégie potentielle pour concevoir du matériel de communication sur des sujets complexes tels que la santé ou l'immunité collective.

Mots clés:

Immunité collective ; immunité de groupe ; vaccination ; hésitation à se faire vacciner ; avatar ; application Web

Abstract

Background: Herd immunity or community immunity refers to the reduced risk of infection among susceptible individuals in a population through the presence and proximity of immune individuals. Recent studies suggest that improving the understanding of community immunity may increase intentions to get vaccinated.

Objective: This study aims to design a web application about community immunity and optimize it based on users' cognitive and emotional responses.

Methods: Our multidisciplinary team developed a web application about community immunity to communicate epidemiological evidence in a personalized way. In our application, people build their own community by creating an avatar representing themselves and 8 other avatars representing people around them, for example, their family or coworkers. The application integrates these avatars in a 2-min visualization showing how different parameters (e.g., vaccine coverage, and contact within communities) influence community immunity. We predefined communication goals, created prototype visualizations, and tested four iterative versions of our visualization in a university-based human-computer interaction laboratory and community-based settings (a cafeteria, two shopping malls, and a public library). Data included psychophysiological measures (eye tracking, galvanic skin response, facial emotion recognition, and electroencephalogram) to assess participants' cognitive and affective responses to the visualization and verbal feedback to assess their interpretations of the visualization's content and messaging.

Results: Among 110 participants across all four cycles, 68 (61.8%) were women and 38 (34.5%) were men (4/110, 3.6%; not reported), with a mean age of 38 (SD 17) years. More than half (65/110, 59.0%) of participants reported having a university-level education. Iterative changes across the cycles included adding the ability for users to create their own avatars, specific signals about who was represented by the different avatars, using color and movement to indicate protection or lack of protection from infectious disease, and changes to terminology to ensure clarity for people with varying educational backgrounds. Overall, we observed 3 generalizable findings. First, visualization does indeed appear to be a promising medium for conveying what community immunity is and how it works. Second, by involving multiple users in an iterative design process, it is possible to create a short and simple visualization that clearly conveys a complex topic. Finally, evaluating users' emotional responses during the design process, in addition to their cognitive responses, offers insights that help inform the final design of an intervention.

Conclusions: Visualization with personalized avatars may help people understand their individual roles in population health. Our app showed promise as a method of communicating the relationship between individual behavior and community health. The next steps will include assessing the effects of the application on risk perception, knowledge, and vaccination intentions in a randomized controlled trial. This study offers a potential road map for designing health communication materials for complex topics such as community immunity.

Keywords:

Community immunity; herd immunity; vaccination; vaccine hesitancy; avatar; web application

Introduction

Background

Herd immunity or community immunity refers to the reduced risk of transmission of infection among susceptible individuals in a population through the presence and proximity of immune individuals. Community immunity (the term we use throughout this paper) works by breaking the chain of transmission and decreasing the probability of contact with an infectious agent, thereby preventing the spread of infectious agents in susceptible populations [1,2]. High vaccination coverage is generally needed to achieve this protection at the population level [3]. Decisions not to vaccinate affect population-level vaccine coverage and can result in outbreaks of vaccine-preventable diseases by pushing the vaccine coverage rate below the community immunity threshold [4-6].

Although some research suggests that people's immunization decisions are primarily influenced by perceived benefits and harm at the individual level rather than those at the community level [7], other studies have suggested that improving the understanding of community immunity may lead to an increase in the intention to be vaccinated [8-10].

Community immunity is a challenging concept to convey. It depends on multiple factors, namely, vaccine effectiveness and coverage, whether or not susceptible individuals form clusters, timing of vaccine administration (ie, delayed vaccination results in longer periods of susceptibility and therefore increased likelihood of infection), and the presence or absence of serotype replacement [11]. It is also affected by historical rates of vaccination coverage where there are potential immunity gaps among people in specific age groups (eg, adolescents and young adults for MMR [measles, mumps, and rubella] vaccines). Possibly because the interplay between all these variables is complicated, people demonstrate an uneven understanding of the connection between individual-level vaccination behavior and community-level risk and benefits [12].

A systematic review identified visualization as a promising avenue for communicating the complex concept of community immunity [13]. By visualization, we mean the visual presentation of data or information. Visualization is a powerful communication mechanism because it enables people to rapidly understand complex information [14]. In this paper, we use the term visualization to refer to a brief narrated animation about community immunity. We use the term application when referring to a complete web-based application, combining the visualization with an interactive section in which people make their own avatars.

Objectives

In this study, we seek to iteratively develop an application about community immunity that would be understood by people with varying levels of education and to assess and optimize people's cognitive and emotional responses to the application. Our focus included emotions because emotions influence people's decisions [15-17], including health decisions [18-20], and specifically vaccination decisions [21,22].

Our study aims to determine (1) whether and how people attend to different visual elements to explain the concept of community immunity (what is community immunity and how it works), (2) whether these elements are understandable, and (3) whether people understand how community immunity safeguards people, especially vulnerable populations who cannot be vaccinated or who may not respond to vaccines owing to their age or suppressed immune system.

Methods

Ethics Approval and Consent to Participate

This project was approved by 'Comité d'éthique de la recherche en sciences de la santé' ethics committee of Laval University (approval no: 2017-137 R-2/15-07-2019). All participants provided written informed consent.

Concept Map

Before designing the first prototype, our multidisciplinary team began by developing a concept map [23] of what the prototype should convey (Multimedia Appendix 1) [in thesis: Appendix 3]. Concept maps are defined as tools for organizing and representing knowledge [24] or a graphical representation of different concepts and the relationship between those concepts [25]. Our concept map was used to organize the underlying content presented in the visualization within three major themes: (1) community, (2) infection, and (3) vaccines. We expanded and refined the components of each theme throughout the study in response to participants' feedback. The theme community included content about how a community is made up of individuals, including vulnerable people living among other individuals. The theme infections included content about how different pathogens cause different infections and spread at different rates. The theme vaccines included content about how effective vaccines may or may not be, how some vaccine effectiveness may wane over time, and how different diseases require different vaccine coverage to prevent the spread of infection and to create community immunity.

Overall Approach

We developed our prototype application according to the concept map and predefined our communication goals for each element of the prototype. Each element of the prototype was linked to what it was intended to convey in the concept map, and what cognitive and/or affective (emotional) responses we aimed to evoke among participants. Across multiple iterative cycles (Multimedia Appendices 2-5) [in thesis: Appendix 4-7], we then measured participants' responses to assess the extent to which each element of our application met its associated communication goals. In each cycle, we further sought to understand participants' needs, strengths, and limitations; observe how they attended to visual elements and colors; and identify potential improvements that could be made to the application.

Framework

To design our application and interpret people's responses, we developed an integrated framework, as shown in Figure 15 (section 3.5), combining four existing frameworks or models: (1) the Health Belief Model [26], (2) Gestalt visual principles [27], (3) the Cognitive Theory of Multimedia Learning [28,29], and (4) Affect Heuristic [30,31].

We selected the Health Belief Model [26] as the most likely framework to help us understand potential health behavior as a result of exposure to our intervention. This model has been developed and used to assess behavioral changes among people. However, this model hypothesizes that the intention or likelihood of an individual to take action stems from individual perception, and there is less detail regarding how such perceptions are shaped by different cues to action. We augmented this model to better understand the antecedents of perception by using Gestalt visual principles to inform the design of our visualization. Gestalt visual principles emphasize that the whole cannot be determined by simply knowing the individual pieces but emerges through how the pieces are combined or structured. These principles can be used to understand how the structure, configuration, or layout of elements in a visualization influence how people perceive the visualization. For example, the figure-ground principle describes how humans perceive objects or figures according to the contrast between elements and their backgrounds, and the proximity principle describes how images or figures located near each other are considered as a part of the same group, whereas objects apart are perceived as separate. Gestalt visual principles can thus help predict the effects of spacing, timing, and configuration when presenting information visually [32]. The Cognitive Theory of Multimedia Learning describes how people learn via two channels—auditory and visual—and use both together to build mental representations from words (audio) and images (visual) [28,29]. Finally, the Affect Heuristic provides an explicit framework for how the experiential system influences decisions via affect and emotions. The experiential system encodes reality in images, metaphors, and narratives, to which people have affective responses [31]. The Affect Heuristic helps structure analyses of emotions in response to the visualization.

Our guiding methodological framework was that of a user-centered design [33] in which potential users are consulted early and often, with their responses to prototype versions serving to help guide iterative improvements of the intervention or tool.

Study Participants and Setting

Across all four study cycles, we recruited participants who were aged 18 years or older, had either no vision problems or corrected vision problems (eg, using eyeglasses or contact lenses), and were able to provide written informed consent, read and understand French or English, and use computers. In cycles 1, 3, and 4, we recruited participants to come to our university-based human-computer interaction laboratory by sending invitations to a university-wide listserv directed at all students, staff, and others. In cycle 2, we recruited participants in person by approaching them at a university-based cafeteria. In cycle 3, in addition to the listserv recruitment, we also recruited participants in person at a public library and two shopping malls located in areas of the city whose postal codes are associated with more diverse educational backgrounds. An incentive of either Can $10 (US $7.46; cycles 1, 2, 4) or Can $20 (US $14.92; cycle 3) was offered for their time and any transportation costs incurred. In cycle 3, we offered a larger incentive because, after viewing our visualization, participants subsequently interacted with materials developed for other studies, meaning that the individual sessions were of a longer duration.

Psychophysiological Measurement

Design cycles 1, 3, and 4 used four psychophysiological data collection methods: eye tracking, galvanic skin response, electroencephalogram (EEG), and facial emotion recognition. We used eye tracking to determine what people were looking at and to measure participants' visual attention [34]. We used galvanic skin response to determine when participants experienced peaks in emotional arousal [35]. Such peaks indicate instances of strong emotions. We expected the visualization to elicit strong emotions when, for example, something alarming happened, such as a vulnerable person getting infected with a contagious disease. We used facial emotion recognition software to assess emotional valence (ie, whether emotions were positive or negative) [36]. We expected participants' emotions to be positive when the visualization depicted positive things happening, for example, community immunity being achieved and protecting community members, and to be negative when the visualization depicted negative things happening, for example, an infection spreading in the community. We used EEG to assess participants' cognitive workload and engagement while looking at the information provided in the visualization [37]. We aimed for participants to experience higher engagement when interacting with the visualization without exceeding a cognitive load threshold above which they might be less likely to process new information.

Apparatus and Procedures

As shown in Figure 16 (page 54), participants sat in a stationary chair in front of a desk with a mobile eye tracker (Tobii X2-30) and a webcam mounted on the computer monitor, a keyboard, a mouse, and computer speakers. A member of the research team explained each participant-worn device while placing it. These participant-worn devices were a portable galvanic skin response apparatus (Shimmer Sensing Shimmer3 GSR+) worn on the participant's nondominant hand and an EEG (Advanced Brain Monitoring B-Alert X-Series) fitted on the participant's head, using a gel on the electrodes. We followed standard procedures for each device's calibration [38-41]. Data streams for all devices were synchronized and saved using the iMotions Attention Tool version 7 (cycle 1) or version 8 (cycles 3 and 4) [42].

Verbal Feedback

We complemented psychophysiological data on participants' nonverbal reactions with brief verbal feedback. Using semi structured interview questions (Multimedia Appendices 6-8)[in thesis: Appendix 8-10], we asked participants to summarize in their own words what they saw in the visualization, what message it aimed to convey, and anything they found confusing or unclear. They were also asked questions about how to improve the visualization or personalized avatar building. If their explanation about the visualization indicated that they may have missed some visual elements, we probed for more specific information on how to improve those visual elements. We recorded responses using an audio recorder and took notes. Table 1 [in thesis: Table 1] shows the summarized study design.

Analysis

Our analytical aim was to assess whether the application achieved its communication goals. To analyze psychophysiological measurements, we examined participants' reactions to each element according to its associated communication goal. We first identified the periods of each element in the visualization according to the voice-over timing. We assessed whether the participant was visually attending to each element by defining an area of interest for each element (eg, a rectangular region around a symbol) and examining whether the participant had any eye fixations of 200 ms or more in that area of interest. Fixations are described in the literature as lasting from 100 to 500 ms [43,44], 150 to 600 ms [45], or as low as 100 ms but typically 200 to 600 ms [46]. We selected 200 ms to maximize the likelihood of detecting fixations among people viewing a rapidly moving visualization while avoiding contaminating our data with shorter pauses in eye movement that might not indicate the person extracting any visual information. During the times when the element was present, we then also examined galvanic skin response, facial emotion, and EEG data as predefined for each communication goal. To analyze the galvanic skin response, we used an algorithm to detect peaks in arousal [47]. Previous literature suggests that this algorithm performs well in detecting such peaks [48,49]. To account for known lags in galvanic skin response (ie, the fact that skin response lags behind experience of heightened arousal by 3 to 5 s [50]), we inspected data for peaks in arousal during the defined time for each communication goal and for an additional 5 s afterward. The existence of such peaks would indicate that the participant experienced a heightened emotion of some kind while that element was displayed. For instance, in the first cycle, some participants showed a peak in arousal when the visualization showed vulnerable people getting infected. To analyze facial emotions, we used the facial recognition software FACET (Emotient) within the iMotions Attention Tool [51]. This software uses algorithms to translate the movement of facial features, such as eyes, eye corners, brows, mouth corners, and nose tip, into classifications of emotional valence. Recent work suggests that this automated facial-expression analysis software performs well for detecting emotional states [52,53]. We inspected the aggregated data for the number of occurrences across all respondents, and for any positive, negative, or neutral emotional valence elicited by the visualization. To analyze the EEG data, we used algorithms to estimate participants' cognitive workload and engagement [39]. Cognitive workload indicates the extent to which working memory is being used. Engagement indicates a participant's attentiveness while watching the visualization. Previous studies have validated these algorithms for measuring cognitive workload and engagement [54-56]. Cognitive workload is reported on a continuous scale from 0 to 1, with 0 to 0.4 classified as boredom, 0.4 to 0.7 as optimal workload, and 0.7 and above as information overload. Engagement levels are also reported on a continuous scale from 0 to 1, with 0 to 0.1 classified as sleepiness and drowsiness, 0.3 as distraction, 0.6 as low engagement, and 0.6 to 1 as high engagement. A summary score was computed by averaging values for each communication goal across all participants. For cycles with fewer than 10 participants, we examined emotional valence and EEG data at the individual level only. For cycles with 10 or more participants, to summarize data while continuing to weigh data from each participant equally, we calculated the mean valence, cognitive load, and engagement for each participant for each element, and then computed summary statistics and indices of dispersion across all participants. When these mean values were normally distributed across participants, our summary statistic was a global sample mean and our index of dispersion was a sample SD. When these mean values were skewed across participants, our summary statistic was a global sample median and our index of dispersion was an IQR. In addition to analyses by area of interest, we also inspected the heat maps of full screens. Heat maps are visual representations of data showing the relative intensity of participants' visual attention to see where participants are looking at the most.

To analyze verbal feedback, two independent analysts (HH and EP) examined the responses independently and assessed the extent to which responses aligned with communication goals for each cycle by deductively comparing participant responses to our detailed concept maps. Any disagreement was resolved through discussion with the senior author (HW). We noted anything that failed to align with communication goals or was confusing to participants to guide changes for the next cycle.

After collecting data for each cycle, the first author (HH) compiled and reviewed data with coauthors (EP and MTB), summarized problems, and drafted recommendations. These recommendations were then discussed with the senior author (HW) and, when necessary, the larger team (remaining authors) to determine changes for the next cycle.

Iterative Cycles

First Cycle

Our multidisciplinary team developed the first version of a visualization based on epidemiological evidence that we had organized in the concept map. We prespecified communication goals for different visual design elements (ie, what we wanted to convey with each element of the visualization and how we expected people to respond). We used four devices (Figure 16) and brief verbal feedback (audio-recorded) to assess participants' interpretations and reactions to the content of the visualization. After viewing, the participants described the visualization in their own words. They were also asked the following questions: What do they think this visualization wants to convey? Is there anything in the visualization that they find unclear or confusing?

Second Cycle

We developed a revised version of the visualization based on participants' feedback in the first cycle. We predefined our communication goals for the second cycle (Multimedia Appendix 9) [in thesis: Appendix 11] and refined the concept map by adding how different diseases spread differently (pertussis, measles, and influenza as test case) and that different diseases require a different number of vaccine doses (e.g., a single dose, multiple, booster, or annual doses). The visualization showed how different parameters (eg, vaccine coverage and intra community contact) can influence community immunity. We audio-recorded a brief verbal feedback.

Verbal Feedback

In this cycle, we only used audio-recorded verbal feedback (no psychophysiological measurements were used in this cycle (Table 1) [in thesis Table 1] to assess participants' interpretations of the visual content and their suggestions to improve it. We chose this method to increase the richness of verbal responses for each visual element. We asked participants to describe their understanding of the visualization, how vaccines work to protect people from diseases, what it means to be immune, and if there was anything confusing or unclear in the visualization. We showed images from the visualization to participants and asked specific questions (eg, what do the icons of the older woman and the baby represent in this visualization? What do the images of viruses causing different diseases represent?). We also asked participants about different terms used to explain community immunity, that is, herd immunity, community immunity, and community protection and which term they prefer.

Third Cycle

We developed a third version of a visualization based on participants' feedback in the second cycle. We used the same techniques as in the human-computer interaction laboratory described earlier, along with verbal feedback. The third cycle was tested in two different settings: a university and different locations in a community setting (two shopping malls and a public library). We predefined the communication goals for the third cycle (see Multimedia Appendix 10 for university sample [in thesis: Appendix 12]and Multimedia Appendix 11 for community sample [in thesis: Appendix 13]). We asked participants to describe, in their own words, the visualization shown to them. We included a larger number of participants in this cycle, as our visualization was closer to launch and we wanted to make sure that it was easily understood and that people grasped the concept of community immunity. We also wanted to test if our communication goals were achieved among people with varied levels of education.

Fourth Cycle

By the fourth cycle, the content of our visualization had achieved nearly all predefined communication goals. However, one major issue remained. Up to this cycle, we had used generic avatars in our visualization. On the basis of data from previous cycles, we were concerned about the extent to which people could identify with the generic avatars presented in the visualization. Therefore, we developed an additional piece in which people were asked to build their own communities by making personalized avatars (their own, 2 vulnerable people in their community, and 6 avatars of people around them who could be family members or coworkers). We added this feature so that people could better identify with the avatars that were subsequently integrated into our application to explain community immunity. We asked participants to provide critical feedback on the process of creating their own avatars and building their own communities. In this cycle, we focused on three questions related to the new features: (1) Was an onboarding tutorial describing how to build avatars a useful addition? (2) Was it easy to build the avatars? and (3) Was the length of the avatar-building process reasonable? We further asked what participants thought of the avatar-building options, including the accessories and color palettes for skin tone and hair color. Participants also described the application in their own words. We only used the eye-tracking device in this cycle to assess visual attention.

Results

Study Participants

A total of 110 eligible participants across the four cycles (cycle 1 [n=8], cycle 2 [n=11], cycle 3 [n=83], and cycle 4 [n=8]) participated in the study (Table 2) [in thesis: Table 17]. Overall, 61.8% (68/110) of the participants were women and 34.5% (38/110) were men; 3.6% (4/110) did not report their gender. The mean age was 38 years (SD 17). Furthermore, 96.3% (106/110) of the participants spoke and understood French, 29.0% (32/110) spoke and understood English, whereas 3.6% (4/110) did not report the language spoken. More than half of the participants (65/110, 59.0%) had a university-level education. Most participants (85/110, 77.2%) reported no physical disability, 16.3% (18/110) reported some form of disability, and 2.7% (3/110) preferred not to answer. Across the 110 participants, 3 (2.7%) did not complete the sociodemographic questionnaire.

Table 17: Sociodemographics of each cycle

Demographic characteristic	**First cycle (n=8)**	**Second cycle (n=11)**	**Third cycle (university sample; n=49)**	**Third cycle (community sample; n=34)**	**Fourth cycle (n=8)**	**Across all cycles (N=110)**
Self-identified gender, n (%)						
Female	3 (38)	7 (64)	34 (69)	16 (47)	8 (100)	68 (62)
Male	2 (25)	4 (36)	15 (31)	17 (50)	0 (0)	38 (35)
Not reported	3 (38)	0 (0)	0 (0)	1(3)	0 (0)	4 (4)
Age (years), mean (SD)	28 (8)	24 (7)	37 (13)	52 (15)	26 (8)	38 (17)
Language, n (%)						
French	5 (63)	11 (100)	48 (98)	34 (100)	8 (100)	106 (96)
English	5 (63)	10 (91)	14 (29)	1 (3)	2 (25)	32 (29)
Not reported	3 (38)	0 (0)	1 (3)	0 (0)	0 (0)	4 (4)
Physical disability, n (%)						
Yes	0 (0)	0 (0)	9 (18)	9 (26)	0 (0)	18 (16)
No	5 (63)	11 (100)	40 (82)	21 (62)	8 (100)	85 (77)
Not reported	3 (38)	0 (0)	0 (0)	1 (3)	0 (0)	4 (4)
Prefer not to answer	0 (0)	0 (0)	0 (0)	3 (9)	0 (0)	3 (3)
Education level, n (%)						
Some elementary School	0 (0)	0 (0)	0 (0)	4 (12)	0 (0)	4 (4)
High school diploma	0 (0)	0 (0)	2 (4)	9 (26)	1 (13)	12 (11)
College or polytechnic school certificate or diploma	1 (13)	4 (36)	8 (16)	6 (18)	3 (38)	22 (20)

(CÉGEP[a], AEC, DEC)						
University graduate degree (bachelor's)	1 (13)	2 (18)	14 (29)	9 (26)	1 (13)	27 (25)
University graduate degree (master's)	3 (38)	5 (45)	20 (41)	1 (3)	3 (38)	32 (29)
University graduate degree (doctorate)	0 (0)	0 (0)	5 (10)	1 (3)	0 (0)	6 (5)
Do not know	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Prefer not to answer	0 (0)	0 (0)	0 (0)	3 (9)	0 (0)	3 (3)
Not reported	3 (38)	0 (0)	0 (0)	1 (3)	0 (0)	4 (4)

[a]Quebec educational level requiring 2 years of study after completion of grade 11. CÉGEP students are typically 17 to 19 years old, and students typically must complete CÉGEP to be admitted to university.

First Cycle

Findings From This Cycle

We obtained psychophysiological data from 6 of 8 participants and qualitative verbal feedback from 8 of 8 participants. There were missing psychophysiological data for 2 participants because of technical issues with the devices. Specifically, we had problems initializing the EEG.

As described in Table 3 [in thesis: Table 18], the design elements of the visualization achieved their communication goals to varying degrees. All participants (8/8) reported that people in clusters of hexagons represented members of the community. Most participants (7/8) reported that a yellow background indicated vulnerable people, and 6 of 6 participants responded psychophysiologically in desired ways, that is, peaks in arousal, and high engagement when a vulnerable person became infected. All participants (8/8) reported that red connecting lines represented the spread of infection. Half of the participants (3/6) did not visually attend to the appearance of a thick blue band indicating community immunity upon its appearance. When questioned about its meaning, most participants (6/8) reported that the blue band around vulnerable people meant community immunity, whereas 2 of 8 participants interpreted it as some sort of linkage between the older woman and the baby. All participants

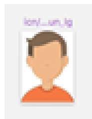
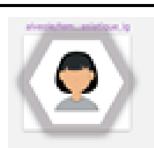
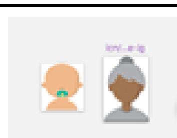
(8/8) explicitly mentioned in their explanation that when enough people were vaccinated, this created a protective barrier of community immunity to prevent the spread of infection. Overall, all participants had a neutral (6/6) facial expression when community immunity was explained in the visualization.

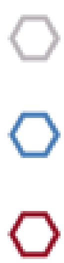
Changes for the Next Cycle

A number of aspects of the first version of the visualization needed improvement. First, only a few participants (1/6) visually attended to the appearance of the central avatar, and only half of the participants (4/8) reported that the central avatar represents them. Second, most people (5/8) did not understand that the avatars around them could be others they see often but who are not members of their immediate family, for example, coworkers. To address these two issues, for the next cycle, we presented the center avatar, immediate family members, colleagues, and other regular contacts in the same visual frame by zooming in and out. Third, participants showed either low engagement (2/6) or drowsy or unengaged (4/6) when an infection first entered the community. To address this, rather than having the infection simply appear, we used a red line to visually represent the entry and spread of infection in the community. Fourth, participants (8/8) suggested that the visualization came across as a simple promotion of immunization rather than explaining how community immunity works. Although these concepts are interrelated in the sense that community immunity requires sufficient numbers of people to be immunized, our goal was to explain community immunity. To address this issue, we increased the focus on community immunity in the narration of our visualization. In discussing this latter change among our team, we identified a need to test the terms herd immunity, community protection, and community immunity by asking participants in the next cycle about their reactions to each of the three terms. In our team discussions, we also identified the need for new visual elements about different viruses (using measles, pertussis, and influenza as examples) to explain in greater detail why different diseases require vaccine doses and schedules.

Table 18: The communication goals set for the first cycle of visualization

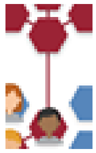
S. no.				

	Design element or a concept	Message design elements intended to convey in the visualization (desired interpretation and/or reaction)	What users reported when viewing these design elements (verbal feedback; n=8)	How users reacted to these design elements (psychophysiology; n=6)
1.		The avatar represents the participant.	Of 8 participants, 4 reported that the avatar represents them. The other 4 participants interpreted it as representing a person, but not them.	Of 6 participants, 1 visually attended to the appearance of the avatar. Overall valence was positive across the 6 participants.
2.		The hexagonal shape represents a unit.	Of 8 participants, 2 reported that each hexagonal shape was a separate unit. The other 6 participants interpreted it as an unspecified symbol or a honeycomb.	N/A (no psychophysiology data specific to this visual element).
3.		A person in a hexagonal shape around the central avatar represents the participant's regular contacts (family members, friends, neighbors, or colleagues).	Of 8 participants, 3 reported that a person in hexagonal shape was a member of their community; 5 participants interpreted it as their family member.	N/A (no psychophysiology data specific to this visual element).
4.		· Icon of an older woman and a baby represents vulnerable people or	All participants (8/8) reported that an older woman and a baby in the visualization represent	Of 6 participants, 4 visually attended when vulnerable people

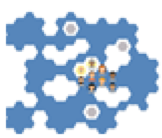
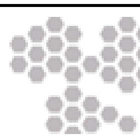
		those with fragile immune systems (eg, patients with cancer). · High arousal and visual attention were expected when vulnerable people appeared in the visualization.	vulnerable people.	appeared in the visualization. Of 6 participants, 3 showed a peak in arousal when vulnerable people appeared.
5.	Yellow color behind *baby* and *an older woman*	Yellow color signals vulnerable people.	Of 8 participants, 7 reported that yellow color signals vulnerable people; 1 participant did not pay attention to the yellow color in the visualization.	N/A (no psychophysiology data specific to this visual element).
6.		Red color signals diseased or infected; blue color signals vaccinated or protected; gray color signals susceptible to disease or infection	· All participants (8/8) reported that the red color in the visualization represents disease, infection, or danger. · All participants (8/8) reported that the blue color in the visualization signals being safe from diseases or vaccinated.	N/A (no psychophysiology data specific to this visual element).

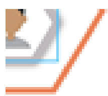
			· Of 8 participants, 6 reported that gray color signals being susceptible to disease/infection or not vaccinated; 2 interpreted gray color as people who can be vulnerable.	
7.	When infection first enters the community.	High arousal, engagement, and visual attention were expected when the visualization shows when the infection first enters the community.	No comments recorded.	· Of 6 participants, 3 visually attended when infection first entered the community. · Of 6 participants, 2 showed a peak in arousal when infection first entered the community. · No participants (0/6) were most likely to be in a high-engagement state when the infection first

				entered the community; 2 of 6 participants were most likely to be in a low-engagement state; 4 of 6 participants were most likely to be in a drowsy (unengaged) state.
8.	When the central avatar gets infected.	High arousal, engagement, and visual attention were expected when the visualization shows the central avatar representing the participant getting infected.	No comments recorded.	· Of 6 participants, 1 visually attended when the avatar got infected. · Of 6 participants, 4 showed peaks in arousal when the avatar got infected. · Of 6 participants, 4 were most likely to be in a high-engagement state when the avatar got infected.

9.		· Red connecting lines represent the spread of infection. · High arousal, engagement, and visual attention was expected when the visualization showed red connecting lines indicating the spread of infection.	All participants (8/8) reported that red connecting lines indicate the spread of infection.	· Of 6 participants, 1 visually attended to red connecting lines. · Of 6 participants, 1 showed peak in arousal when red connecting lines appeared. · All participants (6/6) were most likely to be in a high-engagement state when red connecting lines appeared.
10.	When the vulnerable people get infected.	High arousal, engagement, and visual attention were expected when the vulnerable people got infected.	No comments recorded.	· Of 6 participants, 3 visually attended when vulnerable people got infected. · All participants (6/6) showed a peak in arousal and a negative when

				vulnerable people got infected. · All participants (6/6) were most likely to be in the state of high engagement when vulnerable people got infected.
11.	When community immunity was explained	· Participants' explanations include the concept of community immunity. · High arousal, visual attention, and positive valence was expected when the visualization demonstrated the concept of community immunity.	All participants' (8/8) explanations include the concept of community immunity, that is what it is and how it works.	· Of 6 participants, 4 visually attended when community immunity was explained. · Of 6 participants, 4 showed peak in arousal when community immunity was explained. · Overall facial expression was neutral across the 6 participants.

12.		· Thick blue band around vulnerable people indicates community immunity. · High engagement and visual attention was expected when the thick blue band appeared around vulnerable people.	Of 88 participants, 6 reported that the thick blue band around vulnerable people represents community immunity, which protects them from getting infected.	· Of 6 participants, 3 visually attended when the blue line appeared around vulnerable people. · All participants (6/6) were most likely to be in a high-engagement state when the blue line appeared around vulnerable people.
13.		· Blue lines spreading out from vaccinated people indicate the community immunity. · High engagement was expected when blue lines appeared indicating the community immunity.	All participants (8/8) reported that blue lines spreading out from vaccinated people show the protective barrier that is community immunity.	All participants (6/6) were most likely to be in a high-engagement state when blue lines appeared indicating the community immunity.
14.		The cluster of hexagons represent different communities.	All participants (8/8) reported that clusters of hexagons represent	N/A (no psychophysiology data specific to this

			different communities.	visual element).
15.		The avatar in the cluster of hexagons represents members of the community.	All participants (8/8) reported that the avatar in the clusters of hexagons represents members of the community.	N/A (no psychophysiology data specific to this visual element).
16.		The gray outline around the cluster of hexagons indicates a group or members of the same community.	Of 8 participants, 6 reported that the gray outline indicates the group or members of the same community.	N/A (no psychophysiology data specific to this visual element).
17.		The orange outline showed the participant's community. High engagement was expected when an orange outline appeared around their community.	Of 8 participants, 7 interpreted the orange outline as their community.	Of 6 participants, 3 visually attended when the orange outline appeared around their community. All participants (6/6) were most likely to be in a high-engagement state when the orange outline appeared around their community.

Second Cycle

Findings From This Cycle

The second version of the visualization achieved most of its communication goals. Multimedia Appendix 9 [in thesis: Appendix 11] provides details analogous to those provided in Table 3 [in thesis: Table 18] for the first cycle. All participants (11/11) reported that the people in the hexagon represent members of their community or people with whom they were in daily contact, the older woman and the baby in the visualization represented vulnerable members of the community, and the hexagons represented individuals. Most participants (7/11) reported that the visualization communicated that vaccines are not perfect, and nearly all reported that some vaccines require multiple doses or booster shots to work (10/11). All participants' (11/11) responses showed that they understood the use of colors to signal vulnerability and infection such as a yellow background indicating vulnerable people, and that red color showed propagation of the disease. All participants (11/11) reported that community immunity safeguards vulnerable people, that is, when sufficient number of people around them were vaccinated, whereas lower vaccine coverage puts communities and the people within them, especially vulnerable populations, at risk of becoming sick. Participants indicated that the term community immunity best conveyed the concept compared with terms herd immunity (which implies herds of animals) or community protection (which participants indicated evoked images of protection via firearms.) Few (2/11) participants reported that the color blue indicated immunity, and none (0/11) showed understanding that the color gray indicated susceptibility to infection. Some participants reported that diseases differ (3/11) and spread at different rates (3/11). Few participants (2/11) reported vaccine-induced immunity, whereas none reported the concept of natural immunity (0/11). Some participants (3/11) reported the role of vaccine effectiveness in creating community immunity, whereas others did not.

Changes for the Next Cycle

Aspects of the visualization that needed to be improved included conveying that the color blue means being vaccinated or immune, the color gray means being susceptible, and focusing attention on the fact that different diseases spread at different rates. In addition, the visualization did not yet help participants understand the role of vaccine effectiveness in community immunity or distinguish between natural immunity and vaccine-induced immunity. Participants further suggested that the visualization was too long and provided too much information to retain. In the third cycle, we kept the colors blue and gray but explained their meaning in the narration. We removed the images representing different viruses but kept the narration explaining how different infections spread at different rates, illustrating it with infection spread. We further added depictions of different vaccine coverage for different diseases to show how community immunity prevents the spread of infection. We removed images illustrating natural and vaccine-induced immunity and different vaccine doses, and instead wove this information into the narration illustrated by a single image of immunity. We shortened the visualization for the next cycle to about 2 min and used the term community immunity in the narration.

Third Cycle

Findings From This Cycle

The third cycle mostly achieved its communication goals (see Multimedia Appendix 10 for university sample [in thesis: Appendix 12]and Multimedia Appendix 11 for community sample [in thesis: Appendix 13]). A total of 83 participants (university sample: n=48; community sample: n=34) participated in our third cycle. Most participants (51/83, 61%) reported that the older woman and the baby represented vulnerable people or those with fragile immune systems (eg, patients with cancer). Most participants' (60/83, 72%) verbal feedback summarizing the visualization included the point that vaccines prevent the spread of infection. Most participants (42/83, 50%) reported that community immunity safeguards everyone, some participants (34/83, 41%) reported that the thick blue band around an older woman and the baby demonstrated community immunity protecting vulnerable population and that an individual's decision to get vaccinated or not has an impact on other people in their community (36/83, 43%). Most participants visually attended to all communication goals in a desired way; for example, nearly all participants (80/83, 96%) visually attended when the contagious disease spread to vulnerable people, when vaccines wane over time (74/83, 89%), and when community immunity safeguards everyone (81/83, 97%). Overall, across all 83 participants, people were likely in a state of high engagement and optimal workload during the explanation of how community immunity safeguards everyone.

Changes for the Next Cycle

Results from this cycle suggested that participants mostly understood the information presented in the visualization. However, some wording was unclear, so we made changes to the script to clarify it. For example, in the portion of the animation explaining how vaccines' effectiveness wanes over time, we changed the script from, "They don't work every time, and can wane over time", to, "their protection can fade over time." We also changed the order of some design elements to better align with how people appeared to understand the information during testing. For example, rather than first presenting how different diseases spread at different rates and then explaining community immunity, we changed these to present community immunity first, facilitating the explanation of why some diseases need more people to be vaccinated to create community immunity. Most importantly, until this cycle, we used generic avatars in the visualization. However, the generic avatars continued to be difficult for participants to interpret. To personalize the avatars so that people could better identify with them, we added a functionality so that people could build their own communities by making an avatar for themselves, 2 avatars for vulnerable people in their community, and 6 avatars of other people they see regularly, such as family members or coworkers. These personalized avatars were then integrated into our visualization to help participants better understand and respond emotionally to the idea of family members, friends, or other close contacts being vulnerable and at risk of infection.

Fourth Cycle

We tested the last version of the application with 8 participants. All participants (8/8) reported what community immunity was and how it worked. Participants found the tutorial on how to create avatars confusing and preferred to make avatars by reading instructions. All participants (8/8) were able to easily create avatars by following step-by-step instructions, without a tutorial. All participants liked the color palettes for skin tone and hair colors. A participant suggested adding different accessories with options such as caps, hats, and a hijab to include more culturally diverse and realistic avatars.

The key findings of all cycles and major changes implemented are summarized in Table 4 [in thesis: Table19]

Table 19: Key findings of all cycles and major changes implemented are summarized

Cycles	**Key communication goals achieved**	**Key communication goals not achieved**	**Summary of psychophysiological data (where applicable)**	**Summary of how issues were addressed in the next cycle**

First cycle	• Nearly all participants reported that the color yellow represents vulnerable people. • Most participants reported that the blue band around vulnerable people meant protection. • All participants reported that the avatars in the cluster of hexagons represent members of the community.	• Most participants did not understand that the central avatar represents them. • Some participants did not understand that the avatars around them could include nonfamily contacts, for example, coworkers. • All participants understood the purpose of visualization as promoting immunization rather than explaining the concept of community immunity.	• Most participants visually attended to the appearance of vulnerable people. • Most participants had peaks in arousal and showed high engagement when avatars got infected. • All participants showed high engagement when red lines showed the spread of infection. • Most participants visually attended, and all participants had peaks in arousal and showed high engagement when vulnerable people got infected. • Most participants visually attended and had peaks in arousal when community immunity was explained. • All participants showed high engagement when blue lines around people spreading out from vaccinated people showed community immunity.	• We presented the center avatar, immediate family members, colleagues, and communities in the same visual frame by zooming in and out. • We removed the term immunization in the narration script and focused more on community immunity. • We decided to test the terms herd immunity, community protection, and community immunity by asking participants which term they relate to and prefer. • We added a question to be asked in the next cycle about the shape of hexagons presented in

				the visualization. • We added a new design element in the next cycle explaining how different viruses (eg, measles, pertussis, influenza) spread at different rates and require different vaccine schedules.
Second cycle	• All participants reported that yellow signaled vulnerability. • All participants reported that red signaled infection. • All participants reported that hexagons represent people. • Nearly all participants reported community immunity safeguards vulnerable people when sufficient people around them are vaccinated. • All participants preferred the term community immunity over	• Few participants reported that blue meant vaccinated or immune. • No participants reported that gray meant susceptible. • Most participants did not report that different diseases spread at different rates. • Most participants did not report the role of vaccine effectiveness in community immunity. • Few participants reported vaccine-induced immunity. • None of the participants reported accurate understanding of natural immunity.	• Not applicable	• We removed images of viruses but retained in the narration explanation of how different infections spread at different rates. • We added images about different levels of vaccine coverage to achieve community immunity for different diseases.

	herd immunity or community protection.	• All participants suggested that the visualization should be shorter.		• We removed images about different vaccine doses and natural and vaccine-induced immunity. • We shortened the visualization to about 2 min and used the term community immunity.
Third cycle	• Most participants reported that the older woman and baby avatars represent vulnerable people or those with fragile immune systems. • Most participants reported that vaccines prevent the spread of infection. • Most participants reported that community immunity safeguards everyone. •Some participants reported that the thick blue band around an older woman and the baby shows community immunity	• Nearly all participants found it difficult to identify with the generic avatars.	• Some participants had peaks in arousal when the avatar first appeared. • Most participants had peaks in arousal when the vulnerable population was explained in the visualization. • Some participants had peaks in arousal when the infection first entered the community in the visualization. • Most participants visually attended when the community immunity was shown, along with how it safeguards everyone.	• We added a functionality for people to build their own avatars and their own communities.

	protecting vulnerable populations. •Some participants reported that their decision to get vaccinated or not has an impact on other people in their community.		• Overall, participants showed high engagement and an optimal workload throughout the visualization.	
Fourth cycle	• All participants reported an accurate understanding of what community immunity is and how it works. • All participants reported that community immunity safeguards vulnerable people and everyone in the community. • All participants reported that some infections spread faster and need enough people to get vaccinated to prevent the spread of infections. • All participants found it easy to create avatars by following instructions without a tutorial. • All participants liked the palettes for skin and hair colors.	• For all participants, the avatar creation tutorial was confusing. They preferred to make avatars just by reading the step-by-step instructions. • A participant suggested adding additional accessories such as caps, hats, hijab, and other head and hair coverings.	• Nearly all participants visually attended to the avatar creation elements, including written instructions.	• Head and hair covering options (caps, hats, hijab, turban) were added.

[a] N/A: not applicable

In Table 4 [in thesis: Table19], we summarize quantitative findings by referring to all participants when 100% of participants exhibited this; nearly all: 80% to 99%; most: 50% to 79%; some: 25% to 49%; few: 1% to 24%; no participants: 0%.

Discussion

Principal Findings and Comparison With Previous Literature

Considering our study as a whole, we observed three principal findings. First, visualization does indeed appear to be a promising medium for conveying what community immunity is and how it works. Our project builds on the limited previous literature on visualization to convey the concept of community immunity. On the basis of our systematic review [13], Betsch et al [10] are the only team to have developed and evaluated such an interactive visualization. Their visualization increased vaccination intentions and demonstrated the promise of this medium for conveying the concept of community immunity. We built on this by adding personalization to increase the user's identification with the avatars, a voice-over to increase learning, especially among people with lower literacy, and a focus on the protection of vulnerable members of a community. In addition to previous research by Betsch et al [10,57], other studies have also pointed to the potential advantages of using visualization and videos to convey the concept of community immunity [58,59].

Second, our study shows that by involving users in iterative cycles during the design process, it is possible to create a relatively short and simple visualization that conveys a mathematically complex topic. This aligns with previous literature suggesting that visualizations can support people in understanding complex concepts [60-62], and users' involvement in the design process can facilitate an understanding of the information [63].

Finally, our study shows that considering emotion during the design process can help inform the final design of the intervention. Emotions play an important role in health decision making [17], especially when deciding on behalf of loved ones [64], as is the case when deciding about vaccinating one's children [65]. To the best of our knowledge, no previous study has considered emotions in developing a tool to explain community immunity [13]. In keeping with the Affect Heuristic within our framework, our study explicitly considered emotion, as expressed in verbal feedback and measured with psychophysiological data. According to Peters et al [66], affect has four possible functions in health communication and decision making. Affect can directly influence decisions according to a person's subjective sense of the goodness or badness of options; it can function "as a spotlight" to direct a person's attention toward information, which, in turn, shapes their judgments and decisions; it can motivate information processing and behavior; and it can help people trade-off between concepts that are difficult to compare directly. Because our application is designed primarily to convey a complex concept to inform decisions, we focused on affect's function as a spotlight and adapted our application to better provoke emotional reactions to key information, such as the vulnerability of some community members. Attending to data about participants' emotions throughout the design process therefore helped us carefully adapt our application to the way people perceive and use information to make health-related or other decisions.

Limitations

This study has four main limitations. First, study participants were primarily French-speaking people in Quebec City, Canada, predominantly women, and many had a relatively high level of education. Our recruitment materials for different cycles mentioned that the study was about vaccination or health, which may have contributed to the over-representation of women in our university-based samples. Women seek health services more frequently than men [67] and are the overwhelming majority of participants in studies on childhood vaccine decision making [68]. To address this, in our largest cycle (third cycle), we expanded our recruitment strategy to include community-based settings. By deliberately recruiting a large subsample from a population that was more likely to include men and more likely to include people with lower levels of education, we were better able to ensure that the final design would be appropriate for a broad audience. However, despite our best efforts to diversify our study sample, our results may not be generalizable to other populations. Second, our application currently requires that users be able to visually perceive presentations on a screen. Further work will ensure accessibility for people who are blind or visually impaired. Third, building avatars and launching an application requires a certain level of computer literacy, meaning that the application will not necessarily serve people who are uncomfortable using or unable to use computers. Finally, the studies included people who were specifically recruited to participate in a study. It remains to be seen whether people are willing to view a 2-min visualization of community immunity outside of a study setting.

Conclusions

Our application shows promise as a method of conveying the concept of community immunity to a broad range of members of the general public. This study has practical implications regarding how to design health communication materials about complex topics, such as community immunity, and other concepts that combine individual and population benefits and harms, such as antibiotic resistance, health resource allocation, and interventions during epidemics. Applications with personalized avatars may be more effective than abstract visual representations or text-based explanations to help people understand their personal role in population health. Further research could evaluate the specific effects of personalization. Our future work will test our application in a web-based randomized controlled trial to assess its effects on risk perception, knowledge, and vaccination intentions.

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Authors' Contributions

HH and HW contributed to the design of the study. HH, EP, and MB contributed to data collection. HH, EP, MB, DA, MN, NT, and HW helped in designing and programming the application. HH and HW drafted the first version of the article. DA, JB, CC, ED, MD, TG, AG, EK, SM, MN, RO, EP, JP, JR, BS, AS, NT, MB, KW, JL, and DR critically revised the article and approved the final version for submission for publication. HH and HW had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Conflicts of Interest

KW is the CEO and founder of CANImmunize, a digital immunization platform.

Abbreviations

EEG: electroencephalogram

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Chapter 7: Results of the third aim to evaluate the effects of the Herdimm application and other interventions on risk perception (primary outcome) and on emotions, trust in information, knowledge, vaccination intentions and antecedents of vaccination (5C scale) (secondary outcomes) among members of the Canadian general public.

Résumé

Objectif: Évaluer les effets d'une intervention visant à communiquer le concept d'immunité collective (immunité de groupe) sur la perception des risques, les émotions, la confiance envers l'information (reçue par rapport à la vaccination ou l'immunité collective), les connaissances et les intentions en matière de vaccination.

Méthodes: Nous avons préalablement développé une application Web montrant le fonctionnement de l'immunité collective en suivant un processus de conception centré sur l'utilisateur et incluant 110 utilisateurs et quatre cycles itératifs. Dans notre application, les utilisateurs doivent créer une communauté virtuelle en personnalisant des personnages visant à les représenter eux-mêmes, puis à représenter huit autres personnes de leur entourage (par exemple des membres de leur famille ou des collègues de travail), incluant deux personnes vulnérables. L'application intègre ensuite ces personnages dans une vidéo animée de deux minutes. La présente étude visait à évaluer cette intervention dans le cadre d'un essai randomisé contrôlé factoriel à plusieurs volets auprès d'adultes au Canada. L'essai visait à répondre à trois questions: 1) Pour quatre maladies évitables par la vaccination (la rougeole, la coqueluche, la grippe et une maladie générique), l'intervention influence-t-elle la perception des risques par rapport à une condition de contrôle (aucune information préalable) ? 2) Pour les quatre maladies évitables par la vaccination, l'intervention influence-t-elle les autres résultats (confiance, complaisance, contraintes, délibération, responsabilité collective, émotions, la confiance envers l'information, connaissances et intentions de vaccination) par rapport à un groupe contrôle ? 3) Comment les effets de l'intervention Herdimm se comparent-ils à ceux des interventions existantes déjà disponibles en ligne ? Mon équipe et moi avons effectué des analyses de variance à deux facteurs pour les variables continues et des régressions logistiques pour les variables dichotomiques. Nous avons exécuté cinq modèles pour chaque analyse : un modèle simple, un modèle ajusté avec des covariables, un modèle de modération utilisant une mesure validée de l'individualisme et du collectivisme, et deux modèles supplémentaires examinant spécifiquement les résultats par niveau d'éducation. Nous avons préenregistré notre essai, et déposé tous les matériaux de l'étude sur l'Open Science Framework le 26 février 2021. Notre matériel préenregistré comprend le questionnaire, le dictionnaire de données et le code statistique en R (version 4.0.1), que nous

avons développé avec des données simulées avant de commencer l'essai. Nous avons commencé l'essai le 1er mars 2021, en collectant les données par vagues successives.

Résultats: Dans l'ensemble, l'intervention Herdimm a eu les effets souhaités sur tous ses objectifs. Plus précisément, en ce qui concerne la compréhension du risque, les personnes assignées à l'intervention Herdimm étaient plus susceptibles d'obtenir un score élevé sur la compréhension des risques perçus (58,0 %, intervalle de confiance de 95 % 56,0 % - 59,9 %) par rapport aux personnes assignées à la condition de contrôle (38,2 %, intervalle de confiance de 95 % 35,5 % - 40,9 %). L'intervention Herdimm a quelque peu augmenté le sentiment de risque perçu, passant d'une moyenne de 5,30 sur une échelle de 1 à 7 chez les personnes assignées au contrôle à 5,54 chez celles assignées à Herdimm. Cette différence semble être attribuable à un effet plus important chez les personnes assignées à la grippe (estimation de la différence = 0,456, erreur standard = 0,0869, degrés de liberté = 3875, rapport $t = -5{,}243$, $p < 0{,}0001$). Les personnes qui ont visionné l'intervention Herdimm étaient plus susceptibles d'indiquer un niveau élevé d'intention de se faire vacciner. En effet, 52,1 % de ces personnes ont indiqué un niveau d'intention de se faire vacciner égal ou supérieur à la médiane (intervalle de confiance de 95 % 50,1 % - 54,0 %), contre 47,0 % des personnes assignées à la condition de contrôle (intervalle de confiance de 95 % 44,1 % - 50,0 %). Les personnes qui ont visionné l'intervention Herdimm étaient plus susceptibles d'indiquer un niveau élevé d'émotions (par exemple, un niveau élevé d'accord avec 5 affirmations telles que : « Je suis inquiet que mon entourage (famille, amis) contracte une maladie évitable par la vaccination » et « Je me sentirais coupable si je transmettais à quelqu'un de mon entourage (famille, amis) une maladie évitable par la vaccination ». La moyenne globale était de 5.07 sur une échelle de Likert allant de 1 à 7 (intervalle de confiance à 95% de 5,02 à 5,13), par rapport aux personnes assignées au groupe témoin qui ont obtenu une moyenne de 4,90 (intervalle de confiance à 95% de 4,83 à 4,98). Enfin, les personnes qui ont visionné l'intervention Herdimm étaient plus susceptibles d'obtenir un score légèrement plus élevé à l'évaluation des connaissances, avec une moyenne de 9,12 sur 15 (intervalle de confiance à 95 % de 9,02 à 9,22), par rapport aux personnes assignées à la condition de contrôle qui ont obtenu une moyenne de 8,58 (intervalle de confiance à 95 % de 8,44 à 8,73). Les modèles de modération ont montré que de nombreux résultats étaient modérés par les scores des participants sur une échelle validée mesurant l'individualisme et le collectivisme. Plus précisément, les participants ayant une orientation plus collectiviste se sont montrés plus réceptifs aux arguments concernant les avantages collectifs d'une vaccination généralisée. Pour la troisième question de recherche où l'intervention de Herdimm a été comparée aux autres interventions disponibles en ligne, les résultats de notre modèle primaire et des analyses du modèle 2 ont montré que, pour la plupart des résultats et pour les maladies rougeole et grippe, les effets des autres interventions étaient similaires ou moindre que ceux de l'intervention Herdimm. Il n'y a pas eu de comparaison pour la coqueluche, car nous n’avons pas trouvé d'intervention liée à cette maladie. Enfin, pour les interventions concernant une maladie évitable par la vaccination générique, deux ont eu des effets plus favorables que ceux de Herdimm, offrant ainsi des pistes d'améliorations de notre intervention.

Conclusions: Transmettre le concept d'immunité collective améliore la perception du risque et influence positivement les intentions de recevoir des vaccins, en particulier chez les personnes qui ont une vision du monde plus collectiviste. Cette étude est encore plus pertinente aujourd’hui, alors que les pays du monde entier mènent des campagnes de vaccination contre la COVID-19.

Abstract

Purpose: To evaluate the effects of an intervention conveying the concept of community immunity (herd immunity) on risk perception, emotions, trust in information, knowledge and intentions regarding vaccination.

Methods: We previously developed an online application showing how community immunity works through a user-centered design process with 110 participants across 4 cycles. In our application, people were asked to personalize a virtual community by adding avatars (themselves, 2 vulnerable people in their community, and 6 other people around them; e.g., family members or co-workers). The application integrates these avatars in a 2-minute narrated animation. The present study is evaluating this intervention in a multi-armed factorial randomized controlled trial among adults in Canada. The trial addresses three questions: 1) Across 4 vaccine-preventable diseases (measles, pertussis, influenza, and a generic "vaccine-preventable disease"), does the intervention influence risk perception compared to a control condition (no education)? 2) Across 4 vaccine-preventable diseases, does the intervention influence other outcomes (confidence, complacency, constraints, calculation, collective responsibility, emotions, trust, knowledge, vaccination intentions) compared to a control? 3) For any of the 4 diseases, how do effects of the Herdimm intervention compare to those of existing interventions already available online? My team and I performed two-way analyses of variance for continuous outcomes and logistic regressions for dichotomous outcomes. We ran five models for each analysis: a simple model, an adjusted model with covariates, a moderation model using a validated measure of individualism and collectivism, and two additional models looking specifically at results by education level. We pre-registered our trial, including depositing all study materials on Open Science Framework on February 26, 2021. Our pre-registered materials include the questionnaire, data dictionary, and statistical code we developed in R (version 4.0.1) with simulated data prior to beginning the trial. We began the trial on March 1, 2021, collecting data in waves.

Results: Overall, the Herdimm intervention had effects in the desired directions on all outcomes. Specifically, with respect to risk perception as comprehension, people assigned to the Herdimm intervention were more likely to score high on risk perception as

comprehension (58.0%, 95% confidence interval 56.0% - 59.9%) compared to those assigned to the control condition (38.2%, 95% confidence interval 35.5% - 40.9%). The Herdimm intervention increased risk perception as feelings somewhat from a mean of 5.30 on a scale from 1 to 7 among those assigned to control to 5.54 among those assigned to Herdimm. This effect appeared to be driven by a larger difference among people assigned to flu (difference estimate = 0.456, standard error = 0.0869, degrees of freedom = 3875, t ratio = -5.243, $p < 0.0001$). People who viewed the Herdimm intervention were more likely to indicate high vaccine intentions with 52.1% of people indicating intentions at or above the median (95% confidence interval 50.1% - 54.0%) compared 47.0% among those assigned to the control condition (95% confidence interval 44.1% - 50.0%). People who viewed the Herdimm intervention were more likely to indicate high emotions (for example, high agreement with 5 items including, "I am worried about people in my life (family, friends) getting a vaccine preventable disease," and "I would feel guilty if someone in my life (a family member, a friend) got a vaccine preventable disease from me") with an overall mean of 5.07 on a Likert scale from 1 to 7, 95% confidence interval 5.02 - 5.13) compared to those assigned to the control condition with mean 4.90 , 95% confidence interval 4.83 - 4.98). Finally, people who viewed the Herdimm intervention were more likely to score slightly higher on knowledge with mean 9.12 out of a possible 15 (95% confidence interval 9.02 - 9.22) compared to those assigned to the control condition with mean 8.58 (95% confidence interval 8.44 - 8.73). Moderation models showed that many findings were moderated by participants' scores on a validated scale of individualism and collectivism. Specifically, overall, participants with more collectivist orientations demonstrated more responsiveness to arguments about the collective benefits of widespread vaccination. For the third research question where Herdimm intervention was compared with the other available interventions online, the results of my primary model and model 2 analyses showed that for most outcomes and for diseases measles and flu, the effects of other interventions were similar or worse than those of the Herdimm intervention. There was no comparison for pertussis, as there were no previous interventions relevant to pertussis. In the case of interventions about a generic vaccine-preventable disease, two other interventions had larger desirable effects than Herdimm, offering opportunities for potential improvements in the Herdimm intervention.

Conclusions: Conveying the concept of community immunity improves risk perception and positively influences intentions to receive vaccines, particularly among people who have more collectivist worldviews. This work is increasingly relevant as countries around the world carry out Covid-19 vaccination campaigns.

7.1 Description of participants' characteristics:

Of 18509 participants who started the study, 5516 participants were eligible for the analysis. Figure 18 shows my CONSORT flow diagram.

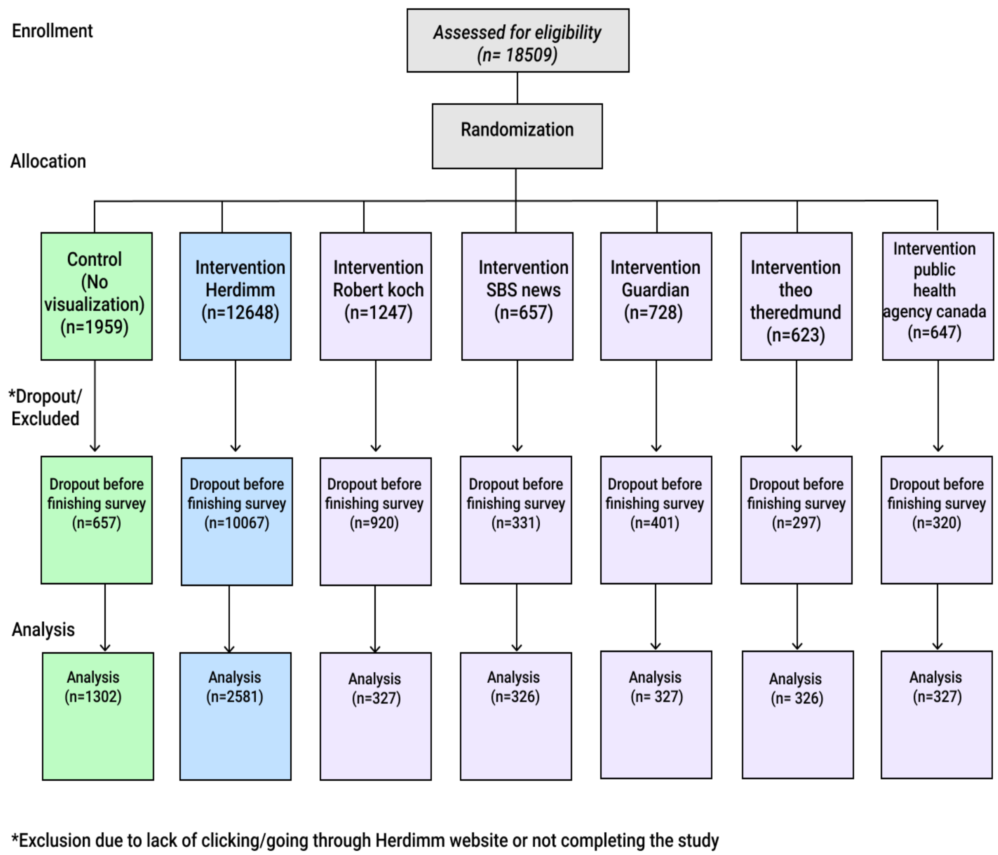

Figure 18: CONSORT flow diagram

Note: Non-applicable elements of the CONSORT template were removed. There was no time interval between intervention allocation and follow-up

Covariate categories containing less than 5% of the final sample (N=5516) within that covariate were collapsed. In other words, any category within a covariate containing fewer than 276 people was collapsed with the closest other category within that covariate to facilitate analysis. If no other category was available (e.g., for gender identity) we coded those data as missing. Specifically, the covariate *ethnicity* was planned to have categories Asian group, Black group, Indigenous group, Maghrebian/Middle Eastern group, and white group. However, due to low counts, categories Black group, Indigenous group, and Maghrebian/Middle Eastern group were eliminated, leaving the categories white group, Asian group and others (Black, Indigenous and Maghreb/MiddleEast). Similarly, the covariate *language* was planned to include French, English and other languages, but due to low counts for other languages, only the French and English categories remained. Along the same lines, to account for low counts in some of the seven *education levels* (elementary school, high School Diploma, apprenticeship or trade certificate or diploma, college or polytechnical school certificate or diploma, university degree, bachelor level or below, university graduate degree (Master's level), university graduate degree (Doctorate level)), we recoded this covariate as *higher* (college degree and above) and *lower* (elementary school, high school diploma, or apprenticeship or trade certificate or diploma) *education*. Finally, due to low counts of people identifying as having a *disability* that affects their ability to use technology like computers, we collapsed this covariate with the larger group of people identifying as having any disability.

Of 5516 participants 50% identified their gender as female and 49% as male. Eighty-five percent were comfortable in communicating in English with their healthcare professional, and 20% in French. Seventy-nine percent of the participants identified themselves as white, a category including white North American and white European. Twelve percent identified themselves as Asian, a category including East, Central, South, Southeast Asian. The remaining 9% included people who identified themselves as Black (4%), Indigenous (3%) and Maghrebian or Middle Eastern (1.3%). Twenty-three percent participants reported a disability of some sort while 75% reported no disability. Fifty-nine percent of the participants reported higher education (college degree or higher) and 40% lower education (no college degree). Table 20 shows details of participant characteristics across the study; Appendix 19 shows participant characteristics and outcomes per study arm.

Table 20: Participants characteristics across the study *(N=5516)*

Participants Characteristics	
Age median (IQR)	42 (32-58)
Place of birth (Canada) n (%)	
Yes	4585 (83%)
No	865 (16%)
NA	66 (1%)

English Language n (%)	
Yes	4665 (85%)
No	846 (15%)
NA	5(0%)
French Language n (%)	
Yes	1102 (20%)
No	4414 (80%)
NA	-
Gender identity n (%)	
Female	2767(50%)
Male	2698(49%)
NA	51 (1%)
Ethnicity Asian n (%)	
Yes	661 (12%)
No	4764 (86%)
NA	91 (2%)
Ethnicity White n (%)	
Yes	4339 (79%)
No	1086 (20%)
NA	91 (2%)
Disability any n (%)	
Yes	1275 (23%)
No	4132 (75%)
NA	109 (2%)
Education levels n (%)	
Higher education (college degree and above)	3263 (59%)
Lower education (elementary school, high school, apprenticeship or trade certificate)	2219 (40%)
NA	34 (1%)

In this thesis, to report results for the first and second research questions of aim 3, I report the results of model 1 as my primary findings. I report the results of model 2 if they differed from those of model 1. I report model 3 if it shows any moderating effects of individualism and collectivism of visualization and disease on outcomes. I report the results of model 4 to discuss any interactions between intervention and education level, and report the results of model 5 when these differed from the results of model 4. Full results of all 5 models are available in Appendix 23-25. Note that when individualism and collectivism are reported, I report according to this scale's four dimensions, as intended by the original scale developers. The Cronbach alpha of each dimension was acceptable to use these dimensions separately. Namely, the Cronbach alpha for each dimension was: Horizontal individualism =

0.757, Vertical individualism = 0.767, Horizontal collectivism = 0.788, and Vertical collectivism = 0.803.

7.2 Results of the first research question:

Research question 1: "Across 4 vaccine-preventable diseases, does the Herdimm intervention influence risk perception compared to a control (no intervention)?"

Risk perception (primary outcome):

I measured risk perception using six ad hoc items (see section Variables: Dependent variables, Table 2) with a pre-planned analysis of whether the first item measured the same construct as the others. The scatter plot (Figure 18) and Bland-Altman test showed that the first item did not measure the same construct as the second through sixth items, so I divided risk perception into two measures: *risk perception as comprehension* (item 1) and *risk perception as feelings* (items 2 to 6). Due to the left-skewed distribution of *risk perception as comprehension*, I then dichotomized this outcome into high (defined as: at or above the median) versus low (defined as: below the median). I combined the second through sixth items into a single measure, *risk perception as feelings*, with Cronbach alpha = 0.761.

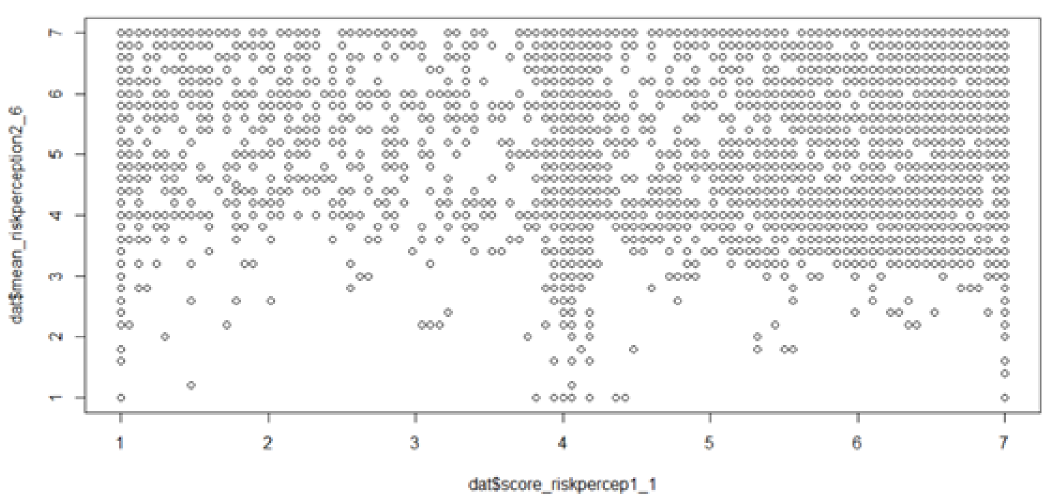

Figure 18: Scatter plot between *risk perception as feelings* (riskperception2_6) and *risk perception as comprehension* (riskpercep1_1)

Risk perception as comprehension:

My primary logistic regression model (section 4.3 Aim 3: Evaluating prototype; Statistical analysis, and Table 10) showed a statistically-significant main effect of the intervention (Herdimm or control) (Chi-squared (1) = 134.54, $p < 0.001$). There was no main effect of disease (measles, pertussis, flu, generic vaccine-preventable disease) (Chi-squared (3) = 6.94, $p = 0.074$), and no statistically-significant interaction between intervention and disease (Chi-squared (3) = 1.19, $p = 0.755$). More specifically, people who were assigned to the Herdimm intervention were more likely to score high on *risk perception as comprehension* (58.0%, 95% confidence interval 56.0% - 59.9%) compared to those assigned to the control condition (38.2%, 95% confidence interval 35.5% - 40.9%).

My second model showed that inclusion of planned covariates did not change results. The effect of the intervention remained significant (Chi-squared (1) = 99.15, $p<0.001$) while the effect of disease and the interaction between intervention and disease remained not significant. My third model showed that individualism and collectivism did not moderate the effects of visualization and disease on *risk perception as comprehension*. My fourth model showed that the Herdimm intervention led to increased likelihood of scoring high on *risk perception as comprehension* among people with lower levels of education (Odds Ratio 1.71, 95% confidence interval 1.35-2.07) and even greater increased likelihood among people with higher levels of education (Odds Ratio 2.66, 95% confidence interval 2.17-3.16). My fifth model showed that this finding was robust to adjustment by covariates. This suggests that the effects of the Herdimm intervention on this outcome differed in magnitude according to level of education. In other words, it was effective among people with lower levels of education and even more effective among people with higher levels of education.

Risk perception as feelings

As shown in Table 21, my primary model showed a statistically significant main effect of the intervention (Herdimm or control), a statistically significant main effect of disease (measles, pertussis, flu, generic vaccine-preventable disease), and a statistically significant interaction between intervention and disease on *risk perception as feelings*. More specifically, *risk perception as feelings* was higher among people who were assigned to the Herdimm intervention compared to those assigned to the control, particularly among people assigned to flu condition (difference estimate = 0.456, standard error = 0.0869, t (3875) = -5.243, p < 0.0001).

Table 21: *Risk perception as feelings* two-way analysis of variance

	Intervention		
Disease	None (Control) mean (95% confidence interval)	Herdimm (Primary intervention) mean (95% confidence interval)	
Generic	5.31 (5.17-5.45)	5.46 (5.36-5.56)	F (3,3875) = 5.6430, p < 0.001
Measles	5.44 (5.30-5.58)	5.61 (5.51-5.71)	
Pertussis	5.39 (5.25-5.54)	5.56 (5.46-5.66)	
Flu	5.06 (4.92-5.20)	5.52 (5.42-5.62)	
	F (1,3875) = 28.7856, p < 0.001		F (3,3875) = 2.8324, p = 0.037

***Abbreviations:* p*, p-value;* F*, F-statistic*

My second model showed that intervention, disease, and their interaction continued to demonstrate statistically significant effects on *risk perception as feelings* after adjustment for covariates, and is driven by the effects of the Herdimm intervention among participants assigned to measles, pertussis and flu. My third model suggested that the increase in *risk perception as feelings* for Herdimm versus control was driven by the responses of people who scored low on vertical individualism (i.e., who disagreed with statements like, "It is important that I do my job better than others,") and low on horizontal collectivism (i.e., people who disagreed with statements like, "I feel good when I cooperate with others.") The third model further suggested that the relationship between participants' horizontal individualism scores (i.e., their agreement with statements like, "I rely on myself most of the time, I rarely rely on others,") and *risk perception as feelings* was negative among those randomized to the flu condition while it was positive among those randomized to other diseases. My fourth and fifth models showed that although there appeared to be a statistically significant effect of the interaction between intervention and education level in model four, it disappeared after adjustment by covariates. This suggests that the effects of the Herdimm intervention did not differ by level of education.

7.3 Results of the second research question:

Research question 2: "Across 4 vaccine-preventable diseases, does the Herdimm intervention influence other outcomes (5C scale, emotions, trust, knowledge, vaccination intentions, COVID-19 vaccine intentions) compared to a control (no intervention)?"

Vaccination intention (secondary outcome):

My primary logistic regression model (section 4.3 Aim 3: Evaluating prototype; Statistical analysis, and Table 10) showed a statistically significant main effect of the intervention (Herdimm or control) (Chi-squared (1) = 9.41, p = 0.002), main effect of disease (measles, pertussis, flu, generic vaccine-preventable disease) (Chi-squared (3) = 15.02, p = 0.002), and no statistically significant interaction between intervention and disease on *vaccination intention* (Chi-squared (3) = 3.72, p = 0.293). More specifically, people assigned to the Herdimm intervention were more likely to score high on *vaccination intention* (52.1%, 95% confidence interval 50.1% - 54.0%) compared to those assigned to the control condition (46.9%, 95% confidence interval 44.1% - 49.6%). People who were assigned to be in the disease flu (46.0%, 95% confidence interval 43.0%-49.1%) were less likely to score high on *vaccination intention* compared to those assigned to a generic 'vaccine-preventable disease' (53.0%, 95% confidence interval 49.3%-56.1%) and measles (53.0%, 95% confidence interval 49.3%-56.1%).

My second model showed that inclusion of planned covariates changed the results. The effect of the intervention became not significant (Chi-squared (1) = 2.69, p=0.10). The covariates with statistically significant effects at the 5% level on *vaccination intention* were age (Chi-squared (1) = 56.646, p<0.001), collective horizontalism (Chi-squared (1) = 46.271 , p<0.001), income (Chi-squared (3) = 42.401 , p<0.001), disability (Chi-squared (1) = 19.7276, p<0.001), vertical individualism (Chi-squared (1) = 6.422 , p= 0.011), horizontal individualism (Chi-squared (1) = 4.261 , p= 0.04), and education level (Chi-squared (1) = 4.141 , p= 0.042). The effect of disease stayed significant after adjustment for covariates

(Chi-squared (1) = 15.78, p<0.001), while the interaction between intervention and disease remained not significant. The third model further suggested that the relationship between participants' vertical individualism scores (i.e., their agreement with statements like, "I rely on myself most of the time, I rarely rely on others,") and *vaccination intention* was positive among those randomized to the flu condition while it was negative among those randomized to other diseases. My fourth and fifth models showed that there appeared to be no significant effect of the interaction between intervention and education level (with and without adjustment by covariates). This suggests that the effects of the Herdimm intervention did not differ by level of education.

COVID-19 vaccination intention among people who had not yet had a COVID-19 vaccine (secondary outcome):

COVID-19 vaccination intention (measured only among people who had not yet had a COVID-19 vaccine, who were 54% of the total sample) showed a statistically significant main effect of the intervention (Herdimm or control) (Chi-squared (1) = 10.49, p = 0.001), no main effect of disease (measles, pertussis, flu, generic vaccine-preventable disease) (Chi-squared (3) = 1.38, p = 0.71), and no statistically significant interaction between intervention and disease on *COVID-19 vaccination intention* (Chi-squared (3) = 0.28, p = 0.964). More specifically, people assigned to the control condition were more likely to score high on *COVID-19 vaccination intention* (53.2%, 95% confidence interval 50.1% - 56.3%) compared to those who were assigned to the Herdimm intervention (46.0%, 95% confidence interval 43.0% - 49.0%). This suggests that by helping people understand community immunity, we run the risk of conveying to those who had not rushed out to get a COVID-19 vaccine as soon as such vaccines were available that they may not need one because they will be protected by those around them.

My second model showed that inclusion of planned covariates showed the same results as of my primary model. That is, the effect of the intervention remained significant (Chi-squared (1) = 14.69, p = 0.0001) and the effect of disease and the interaction between intervention and disease remained not significant. My third model suggested that among participants with lower vertical collectivism (i.e., they were less in agreement with statements like, "It is my duty to take care of my family, even when I have to sacrifice what I want,") and who did not have a COVID-19 vaccine at the time of survey, the intervention Herdimm (which aims to convey how community immunity works) resulted in lower intentions to get a COVID-19 vaccine. My fourth and fifth models showed that there appeared to be no significant effect of the interaction between intervention and education level (with and without adjustment by covariates). This suggests that the effects of the Herdimm intervention did not differ by level of education.

Trust in information (secondary outcome):

This outcome assessed the extent to which participants trusted the information. Since the control condition had no information provided compared to the Herdimm, we did not compare the effect of interventions. Instead, we compared the effects of diseases on *trust in information*.

My primary logistic regression model showed that there was no significant main effect of the diseases on *trust in information* (Chi-squared (3) = 3.1824, p = 0.3643) (Table 22).

Table 22: *Trust in information* two-way logistic regression

Disease	Probabilities (95% confidence interval)	LR Chisq =3.1824, df= 3 p=0.3643
Generic	0.795 (0.760 - 0.825)	
Measles	0.830 (0.800 - 0.857)	
Pertussis	0.813 (0.781 - 0.841)	
Flu	0.827 (0.796 - 0.854)	

Abbreviations: CI, Confidence Interval; **df,** degree of freedom; **p**, p-value; **LR Chisq**, Likelihood ratio tests

My second model showed that inclusion of planned covariates showed the same results as the first model; that is, the effect of disease remained not significant. My third model showed that individualism and collectivism did not moderate the effects of disease on *trust in information.* We did not check Model 4 and 5 for this outcome because the removal of the intervention variable rendered those analyses moot.

Emotions (secondary outcome):

My primary model (section 4.3 Aim 3: Evaluating prototype; Statistical analysis, and Table 10) showed a statistically significant main effect of the intervention (Herdimm or control) ($F(1,3875) = 13.13$, $p < 0.001$), main effect of disease (measles, pertussis, flu, generic vaccine-preventable disease) $F(3,3875) = 78.54$, $p < 0.001$), and no statistically significant interaction between intervention and disease on *emotions* $F(3,3875) = 1.49$, $p = 0.216$. More specifically, people who were assigned the Herdimm intervention were more likely to score high on *emotions* (mean 5.07, 95% confidence interval 5.02 - 5.13) compared to those assigned to the control condition (mean 4.90, 95% confidence interval 4.83 - 4.98). In other words, they were more likely to indicate higher levels of agreement with statements like, "I am worried about people in my life (family, friends) getting a vaccine-preventable disease," and "I would feel guilty if someone in my life (a family member, a friend) got a vaccine-preventable disease from me." People assigned to the generic 'vaccine-preventable disease' condition (mean 5.48, 95% confidence interval 5.39-5.57) had a higher mean score on *emotions* than those assigned to any specific diseases, including measles (mean 4.59, 95% confidence interval 4.50-4.68). People assigned to the pertussis condition (mean 4.79, 95% confidence interval 4.61-4.79) also had lower mean *emotions* than those assigned to flu (mean 5.18, 95% confidence interval 5.09-5.27).

My second model showed that inclusion of planned covariates changed the results. The effect of the intervention became not significant ($F(1,3440) = 2.93$, $p = 0.087$) and the effect of disease remained significant ($F(3,3440) = 75.47$, $p < 0.001$), while the interaction between intervention and disease remained not significant. My third model suggested that the higher mean on *emotions* for the Herdimm intervention was driven by the responses of people who scored low on horizontal collectivism (i.e., people who disagreed with statements like, "I feel good when I cooperate with others") in the generic disease and who scored high on horizontal collectivism (i.e., people who agreed with the above statement) for measles and pertussis. My fourth model showed that the Herdimm intervention led to a higher mean of *emotions* among people with higher levels of education with a mean of 5.18 (95% confidence interval 5.12-5.25) compared to control with a mean of 4.90 (95% confidence interval 4.80-5.01) among people with lower levels of education. My fifth model showed that this finding was robust to adjustment by covariates (Herdimm intervention mean 5.24 (95% confidence interval 5.12-5.35) versus Control mean 5.01 (95% confidence interval 4.89-5.14). This suggests that the effects of the Herdimm intervention on *emotions* were larger among people with higher levels of education.

Knowledge (secondary outcome):

My primary model (section 4.3 Aim 3: Evaluating prototype; Statistical analysis, and Table 10) showed a statistically significant main effect of the interventions ($F(1,3875) = 36.37$, $p < 0.001$), main effect of disease (measles, pertussis, flu, generic vaccine-preventable disease) ($F(3,3875) = 5.20$, $p = 0.001$), and no statistically significant interaction between intervention and disease on *knowledge* ($F(3,3875) = 2.54$, $p = 0.055$). More specifically, people assigned to the Herdimm intervention had higher mean *knowledge* (mean 9.12, 95% confidence interval 9.02 - 9.22) compared to those assigned to the control condition (mean 8.58, 95% confidence interval 8.44 - 8.73). People who were assigned to be in the disease generic had higher mean knowledge than measles (difference estimate = 0.410, standard error = 0.127, $t(3875) = 3.239$, $p = 0.007$) and pertussis (difference estimate = 0.337, standard error = 0.128, $t(3875) = 2.631$, $p = 0.042$). However, those assigned to disease flu had higher mean knowledge than measles (difference estimate = 0.357, standard error = 0.125, $t(3875) = 2.861$, $p = 0.022$).

My second model showed that inclusion of planned covariates changed the results. The effect of the intervention and the effect of disease remained significant, but the effect of the interaction between intervention and disease became significant as well ($F(3,3440) = 3.2962$, $p = 0.0196$). After adjusting for covariates, people assigned to the Herdimm intervention had higher mean *knowledge* than those assigned to the control condition across all the named diseases (measles, pertussis, flu) but not for the generic vaccine-preventable disease. More specifically, participants who were assigned to Herdimm measles (difference estimate compared to control = 0.84; $p < 0.001$), flu (difference estimate compared to control = 0.68; $p = 0.0002$) and pertussis (difference estimate compared to control = 0.51, $p = 0.0065$) had higher mean *knowledge* than herdimm generic vaccine-preventable disease (difference estimate compared to control = 0.08, $p = 0.68$). My third model suggested that the higher mean *knowledge* for the Herdimm intervention was driven by the responses of people who scored low on vertical individualism (i.e., who disagreed with statements like, "It is important that I do my job better than others.") My fourth model showed an interaction between the Herdimm intervention and education levels on *knowledge*. The Herdimm intervention led to higher mean *knowledge* compared to control among people across all levels of education; however, the effect among those with higher education levels (difference estimate = 0.306, standard error = 0.120, t (3848) = -2.557, p = 0.011) was less pronounced than it was among those with lower levels of education (difference estimate = 0.786, standard error = 0.138, t (3848) = -5.707, p <0.0001). My fifth model showed that this finding was not robust to adjustment by covariates, since the interaction was no longer significant (F (1,3439)=1.99902, p=0.158411).

5C Scale (secondary outcome):

I report each of the 5 factors of the 5C scale separately because the internal consistency for the overall scale was low (Cronbach alpha = 0.44). The Cronbach alpha for each sub scale was Confidence = 0.859, Complacency = 0.761, Constraints = 0.825, Calculation = 0.763, and Collective responsibility = 0.777. Each subscale score was dichotomized at the median.

Confidence:

My primary logistic regression model (section Statistical analysis, page 72 and Table 10) showed a statistically significant main effect of the intervention (Herdimm versus control) (Chi-squared (1) = 15.09, p = 0.0001), no main effect of disease (measles, pertussis, flu, generic vaccine-preventable disease) (Chi-squared (3) = 2.23, p = 0.526), and no statistically significant interaction between intervention and disease on *confidence* (Chi-squared (3) = 2.32, p = 0.508). More specifically, people assigned to the Herdimm intervention were more likely to score high on *confidence* (54.9%, 95% confidence interval 53.0% - 56.8%) compared to those assigned to the control condition (48.3%, 95% confidence interval 45.6% - 51.0%).

My second model showed that inclusion of planned covariates did not change the results of the first model; that is, the effect of the intervention remained significant (Chi-squared (1) = 5.15, p = 0.023), the effect of disease and the interaction between intervention and disease remained not significant. My third model suggested that the positive effect of the

Herdimm intervention on *confidence* was driven by the responses of people who scored high on vertical collectivism (i.e., they were more in agreement with statements like, “It is my duty to take care of my family, even when I have to sacrifice what I want.”) The third model further suggested that the relationship between participants’ vertical collectivism scores and *confidence* was negative among those randomized to the control condition while it was positive among those randomized to Herdimm intervention. My fourth and fifth models showed that there appeared to be no significant effect of the interaction between intervention and education level (with and without adjustment by covariates). This suggests that the effects of the Herdimm intervention did not differ by level of education.

Complacency:

My primary logistic regression model (section 4.3 Aim 3: Evaluating prototype; Statistical analysis, and Table 10) showed no main effect of intervention (Herdimm versus control) (Chi-squared (1) = 1.697, p = 0.193), no main effect of disease (measles, pertussis, flu, generic vaccine-preventable disease) (Chi-squared (3) = 0.88, p = 0.830), and no statistically significant interaction between intervention and disease on *complacency* (Chi-squared (3) = 0.75, p = 0.862).

My second model showed that inclusion of planned covariates changed the results. The effect of the intervention became significant (Chi-squared (1) = 4.898, p=0.027). More specifically, people assigned to the Herdimm intervention were more likely to score low on *complacency* (54.3%, 95% confidence interval 50.0% - 59.0%) compared to those assigned to the control condition (50.0%, 95% confidence interval 45.4% - 54.4%). The main effect of disease (Chi-squared (3) = 0.81, p = 0.847) and the interaction between intervention and disease (Chi-squared (3) = 2.72, p = 0.437) remained not significant. My third model showed that individualism and collectivism did not moderate the effects of visualization and disease on *complacency*. My fourth model showed a significant interaction (Chi-squared (1) = 6.67, p = 0.0098) between intervention (Herdimm versus control) and education levels. People with lower levels of education had an increased likelihood of scoring low on *complacency* when exposed to the Herdimm intervention (Odds Ratio = 1.34 (95% confidence interval 1.09-1.65), p=0.005), while there was no such effect among people with higher levels of education (Odds Ratio = 0.94 (95% confidence interval 0.78-1.12)). However, the fifth model showed that the interaction was not significant after adjustment by covariates (Chi-squared (1) = 2.09, p = 0.148), which suggests that the effects of the Herdimm intervention did not differ by level of education.

Constraints:

My primary logistic regression model (section 4.3 Aim 3: Evaluating prototype; Statistical analysis, and Table 10) showed no main effect of intervention (Chi-squared (1) = 1.29, p =0.256), no main effect of disease (measles, pertussis, flu, generic vaccine-preventable disease) (Chi-squared (3) = 0.79, p = 0.853), and no statistically significant interaction between intervention and disease on *constraints* (Chi-squared (3) = 3.94, p = 0.268).

My second model showed that inclusion of planned covariates showed the same results as the first model; that is, the effect of the intervention, disease and the interaction between intervention and disease remained not significant. My third model suggested that the likelihood of low constraints after exposure to the Herdimm intervention was higher for people with low vertical individualism (i.e., who disagreed with statements like, "It is important that I do my job better than others.") My fourth model showed that the Herdimm intervention led to increased likelihood of scoring low on *constraints* among people with lower education levels (Odds Ratio= 1.32 (95% confidence interval 1.07-1.62), p= 0.0098), while Herdimm had the opposite effect (i.e., decreased likelihood of scoring low on *constraints*) among people with higher levels of education (Odds Ratio= 0.70 (95% confidence interval 0.58-0.84), p = 0.0001.) My fifth model showed that this finding was robust to adjustment for covariates among people with lower education levels (Odds Ratio = 1.40 (95% confidence interval 1.09-1.79), p = 0.009), while it was not robust to adjustment for people with higher levels of education (Odds Ratio = 0.88 (95% confidence interval 0.71-1.09), p = 0.23). This suggests that the effects of the Herdimm intervention on this outcome differed according to level of education. In other words, the Herdimm intervention decreased concerns about logistical barriers to vaccination among people with lower levels of education, while having no such effect among people with higher levels of education.

Calculation:

My primary logistic regression model (section 4.3 Aim 3: Evaluating prototype; Statistical analysis, and Table 10) showed no main effect of intervention (Chi-squared (1) = 0.75, p =0.385), no main effect of disease (measles, pertussis, flu, generic vaccine-preventable disease) (Chi-squared (3) = 3.90, p = 0.272), and no statistically significant interaction between intervention and disease on *calculation* (Chi-squared (3) = 3.69, p = 0.297).

My second model showed that inclusion of planned covariates did not change the results of my first model; that is, the effect of intervention, disease and the interaction between intervention and disease remained not significant. My third model showed that individualism and collectivism did not moderate the effects of visualization and disease on *calculation.* My fourth and fifth models showed that there appeared to be no significant interaction between intervention and education level (with and without adjustment by covariates). This suggests that the effects of the Herdimm intervention on this outcome did not differ by level of education.

Collective responsibility:

My primary logistic regression model (section 4.3 Aim 3: Evaluating prototype; Statistical analysis, and Table 10) showed no main effect of intervention (Chi-squared (1) = 0.499, p =0.4796), no main effect of disease (measles, pertussis, flu, generic vaccine-preventable disease) (Chi-squared (3) 5.58, p = 0.134), and no statistically significant interaction between intervention and disease on *collective responsibility* (Chi-squared (3) = 1.489, p = 0.685).

My second model showed that inclusion of planned covariates changed the results. The main effect of the disease became significant (Chi-squared (3) = 13.54, p = 0.004). People who were assigned to the disease flu were less likely to score high on *collective responsibility* than those assigned to measles (Odds Ratio = 0.69 (95% confidence interval 0.52-0.92), p=0.005) and pertussis (Odds Ratio = 0.74 (95% confidence interval 0.55-0.99), p=0.04). My third model suggested that the Herdimm intervention might have a positive effect on *collective responsibility* both among people who scored low on vertical individualism (i.e., who disagreed with statements like, "It is important that I do my job better than others,") and who scored low on horizontal collectivism (i.e., people who disagreed with statements like, "I feel good when I cooperate with others.") My fourth and fifth models showed that there appeared to be no significant interaction effect between intervention and education level (with and without adjustment by covariates). This suggests that the effects of the Herdimm intervention on this outcome did not differ by level of education.

7.4 Results of the third research question:

> *Research question 3: "For any of the 4 diseases, how do effects of the Herdimm intervention compare to those of existing interventions already available online?"*

In keeping with the analytical strategy for this research question (explained on page 72, section Statistical analysis), in this section, I report the results of model 1 as my primary findings. I report the results of model 2 if they differed from those of model 1. Similarly, I report the results of model 4 to discuss any interactions between intervention and education level, and report the results of model 5 when these differed from the results of model 4. I am primarily interested in comparing interventions to each other, not to the control condition; however, whenever I identify differences between two or more interventions, I also report if their estimates fail to differ from that of the control, as this indicates that any differences between interventions are essentially unimportant.

Results of my primary model and model 2 analyses showed that for most outcomes and for diseases measles and flu, the effects of other interventions were similar or worse than those of the Herdimm intervention. There was no comparison for pertussis, as there were no previous interventions relevant to pertussis. In the case of interventions about a generic vaccine-preventable disease, other interventions had larger desirable effects than Herdimm, offering opportunities for potential improvements in the Herdimm intervention. Specifically, the SBS News and Robert Koch interventions led to higher *knowledge and* lower *complacency* and *constraints* than the Herdimm intervention. There was also a difference with respect to *risk perceptions as feelings* in which both SBS News and Robert Koch interventions led to higher values compared to Herdimm, but only among people with higher levels of education. The SBS News intervention also led to higher *trust in information* than both the Herdimm and the Robert Koch interventions. Finally, the Robert Koch intervention led to higher scores on *collective responsibility* than Herdimm, but again, only among people with higher levels of education. Herdimm generated similar or higher *risk as comprehension* for all disease conditions compared to other interventions across all levels of education. Table 23 below provides details.

Table 23: One-way ANOVA and logistic regressions

Disease (Dichotomous variables were reported with percentages)		
Generic 'vaccine-preventable disease'	Measles	Flu
Outcome: *Risk perception as comprehension*		
Herdimm generic (57%, 95% CI***** 53% - 62%) and SBS News generic (56%, 95% CI 50% - 61%) had higher probabilities of high *risk perception as comprehension* compared to Robert Koch generic (44%, 95% CI 39% - 50%.) There was no significant interaction between study arm and education level.	Herdimm measles (58%, 95% CI 54% - 62%) and Guardian measles (45% , 95% CI 40% - 50%) had higher probabilities of high *risk perception as comprehension* compared to TheOtherEdmund measles (40%, 95% CI 35% - 46%). Herdimm measles was different from TheOtherEdmund (Odds Ratio = 0.482, p < 0.0001), whereas there was no difference between Guardian measles and TheOtherEdmund measles (Odds Ratio = 0.822, p = 0.60). There was no significant interaction between study arm and education level.	Herdimm flu (62%, 95% CI 59% - 66%) had higher probabilities of high *risk perception as comprehension* compared to Public Health Agency Canada flu (38%, 95% CI 33% - 43%). There was no interaction between study arm and education level.
Outcome: *Risk perception as feelings*		

SBS News generic (mean 5.85, 95% CI 5.71-5.98) and Robert Koch generic (mean 5.66, 95% CI 5.53-5.80) had higher scores on *risk perception as feelings* compared to Herdimm generic (mean 5.39, 95% CI 5.28-5.50). When examining this by education level, the differences were apparent only among people with higher levels of education.	There was no difference in the effects on *risk perception as feelings* between Herdimm measles (mean 5.61, 95% CI 5.51-5.71), Guardian measles (mean 5.61, 95% CI 5.47-5.75), and TheOtherEdmund measles (mean 5.39, 95% CI 5.26-5.53). There was no interaction between study arm and education levels.	There was no difference in the effects on *risk perception as feelings* between Herdimm flu (mean 5.52, 95% CI 5.42-5.62) and Public Health Agency Canada (mean 5.50, 95% CI 5.36-5.64). There was no interaction between study arm and education level.
Outcome: *Vaccination intentions*		
There were no significant differences between different interventions in generic for *vaccination intentions* (Chi-squared (3) = 2.95, p = 0.3996). When examining this by education level, there was no significant interaction between study arm and education level on *vaccination intentions*.	Herdimm measles (57%, 95% CI 53% - 61%) had higher probabilities of high *vaccination intentions* compared to TheOtherEdmund measles (48% 95% CI 0.422-0.530). However, this difference was not robust to covariate adjustment. There was no significant interaction between study arm and education level on *vaccination intentions*.	There were no significant differences between different interventions in flu for *vaccination intentions* (Chi-squared (2) = 0.33, p = 0.848). There was no interaction between study arm and education level on *vaccination intentions*.
Outcome: *COVID-19 vaccination intentions*		
After adjusting for covariates, there were differences between interventions' effects on *COVID-19 vaccination intentions* (Chi-squared (3) = 8.7824, p = 0.032). Herdimm generic appeared to lead to lower probabilities of high *COVID-19 vaccination intentions* (38%, 95% CI 26%-53%) than Robert Koch generic (44%, 95% CI 30% - 60%). SBS News generic was higher than both Herdimm generic and Robert Koch generic (50%, 95% CI 37%-64%). However, because this outcome was only measured	There were no significant differences between different interventions in measles for *COVID-19 vaccination intentions* (Chi-squared (3) = 4.24, p = 0.236).When examining this by education level, there was no significant interaction between study arm and education level.	There were no significant differences between different visualizations in flu for *COVID-19 vaccination intentions* (Chi-squared (2) = 4.15, p = 0.126). When examining this by education level, there was no interaction between study arm and education level on *COVID-19 vaccination intentions*.

among the subsample of people who had not yet had a COVID-19 vaccine during the study period (Mar-Jul 2021), the wide confidence intervals meant that none of the pairwise comparisons between interventions were significant. When examining this by education level, there was no significant interaction between study arm and education level.		
Outcome: *Trust in information*		
SBS News generic (86%, 95% CI 81% - 89%) had higher probabilities of high *trust in information* compared to Herdimm generic (78%, 95% CI 74% - 82%) and Robert Koch generic (73%, 95% CI 68% - 78%). There was no significant interaction between study arm and education level.	Herdimm measles (83% 95% CI 80% - 86%) and Guardian measles (73%, 95% CI 68% - 77%) had higher probabilities of high *trust in information* compared TheOtherEdmund measles (57%, 95% CI 52% - 63%). There was no significant interaction between study arm and education level.	There were no significant differences between different interventions in flu on *trust in information* (Chi-squared (1) = 0.48482, p = 0.4862). There was no significant interaction between study arm and education level.
Outcome: *Emotions*		
There were no significant differences between different interventions in the generic vaccine-preventable disease condition for *emotions* F(3,1385)= 0.47, p= 0.705. When examining this by education level, there was no significant interaction between study arm and education level on *emotions*.	Herdimm measles (mean= 4.72, 95% CI 4.62-4.83) had higher scores on *emotions* compared to TheOtherEdmund measles (mean= 4.39, 95% CI 4.24-4.54). There were no differences on *emotions* between Guardian measles (mean= 4.64, 95% CI 4.49-4.79) and other study arms. There was no significant interaction between study arm and education level.	There were no significant differences between different interventions in flu for *emotions* F(2,1318)= 2.56, p = 0.077. When examining this by education level, a potential interaction between study arm and education levels was not robust to covariate adjustment.
Outcome: *Knowledge*		
After adjustment for covariates, SBS News generic	Herdimm measles (mean= 9.08, 95% CI 8.88-9.28) had	Herdimm flu (mean = 9.27, 95% CI 9.07-9.46) had higher

(mean= 9.94, 95% CI 9.44-10.45) had higher scores on *knowledge* compared to Herdimm generic (mean= 9.26, 95% CI 8.75-9.77). Robert Koch generic (mean= 9.72, 95% CI 9.18-10.25) did not have different effects on *knowledge* compared to SBS News generic or Herdimm generic. When examining this by education level, there was no significant interaction between study arm and education level on *knowledge*.	higher scores on *knowledge* compared to Guardian measles (mean= 8.33, 95% CI 8.04-8.62) and TheOtherEdmund measles (mean= 8.06 95% CI 7.77-8.35). When examining this by education level, there was no significant interaction between study arm and education level on *knowledge*.	scores on knowledge compared to Public Health Agency Canada flu (mean=8.62, 95% CI 8.34-8.90). When examining this by education level, after adjustment for covariates, this difference was apparent only among people with lower levels of education.
5C subscale		
Outcome: *Confidence*		
There were no significant differences between different interventions in generic for *confidence* (Chi-squared (3) = 5.31, p = 0.151). When examining this by education level, there was no significant interaction between study arm and education level on *confidence*.	There were no significant differences between different interventions in generic for *confidence* (Chi-squared (3) = 5.52, p = 0.137). When examining this by education level, there was no significant interaction between study arm and education level on *confidence*.	There were no significant differences between different interventions in generic for *confidence* (Chi-squared (2) = 1.04, p = 0.595). When examining this by education level, there was no significant interaction between study arm and education level on *confidence*.
Outcome: *Complacency*		
Robert Koch generic (64%, 95% CI 58% - 69%) had higher probabilities of low *complacency* compared to Herdimm generic (49%, 95% CI 45% - 54%). However, neither intervention had different results compared to control (54%, 95% CI 48% - 60%). When examining this by education level, there was no significant interaction between study arm and education.	There were no significant differences between different interventions in measles for *complacency* (Chi-squared (3) = 1.61, p = 0.657). When examining this by education level, there was no significant interaction between study arm and education level on *complacency*.	Herdimm Flu (53%, 95% CI 49% - 57%) had higher probabilities of low *complacency* compared to Public Health Agency Canada flu (44%, 95% CI 39% - 50%). However, neither intervention had different results compared to control (49%, 95% CI 43% - 54%). When examining this by education level, there was no interaction between study arm and education level on *complacency*.

Outcome: *Constraints*		
Robert Koch generic (62%, 95% CI 57% - 67%) had higher probability of low *constraints* compared to Herdimm generic (50%, 95% CI 46% - 54%). However, neither intervention had different results compared to control (58%, 95% CI 52% - 64%). When examining this by education level, there was no significant interaction between study arm and education level on *constraints*.	There were no significant differences between different interventions in measles for *constraints* (Chi-squared (3) = 1.85, p = 0.605). When examining this by education level, there was no significant interaction between study arm and education level on *constraints*.	After adjusting for covariates, Public Health Agency Canada flu (55%, 95% CI 46% - 63%) had lower probability of low constraints than Herdimm flu (66%, 95% CI 58% - 73%) (OR 0.64, 95% CI 0.44 - 0.93). When examining this by education level, there was no significant interaction between study arm and education level on *constraints*.
Outcome: *Calculation*		
There were no significant differences between different interventions in generic for calculation (Chi-squared (3) = 5.35, p = 0.148). When examining this by education level, there was no significant interaction between study arm and education level on *calculation*.	Herdimm measles (61%, 95% CI 57% - 65%) had higher probability of high *calculation* compared to TheOtherEdmund measles (52%, 95% CI 47% - 58%) (Odds Ratio = 0.691, p = 0.034). However, this difference was not robust to covariate adjustment. When examining this by education level, there was no significant interaction between study arm and education level on calculation.	There were no significant differences between different interventions in flu for *calculation* (Chi-squared (2) = 0.09, p = 0.956). When examining this by education level, there was no significant interaction between study arm and education level on calculation.
Outcome: *Collective responsibility*		

Robert Koch generic (60%, 95% CI 55% - 65%) SBS News generic (59%%, 95% CI 54% - 64%) had higher probability of high *collective responsibility* compared to Herdimm generic (47%, 95% CI 42% - 51%). However, neither intervention had different results compared to control (54%, 95% CI 42% - 65%). When examining this by education level, there was no robustly significant interaction between study arm and education level on collective responsibility.	There were no significant differences between different interventions in measles for collective responsibility (Chi-squared (3) = 6.09, p = 0.108). When examining this by education level, there was no significant interaction between study arm and education level on collective responsibility.	There were no significant differences between different interventions in flu for collective responsibility (Chi-squared (2) = 2.66, p = 0.265). When examining this by education level, there was no significant interaction between study arm and education level on collective responsibility.

*CI = confidence interval

Herdimm intervention was recorded in two languages (English and French) and in two voices (male and female). I and my team member have therefore, analysed that *"Are the effects of the Herdimm intervention different when the narration uses a female or male voice?"* Our analysis showed that there were no effects of the gender of the voice, nor interactions with the studyarms and gender identity, on risk perception.

I and a team member have also runned our analysis on primary models for outcomes which had missing values. To do this, fifteen multiple imputation datasets were generated. I and a team member examined whether results with imputed data replicated or contradicted our earlier findings. Many outcomes did not have missing values, and there were no changes from original results for the primary model (Model1) for example., *risk perception as feelings, knowledge, emotion,* and *5C subscales*. This might be because these variables are a function of several items, and even if some items were missing, a mean or sum could still be calculated. For outcomes such as *vaccination intention, trust in information and risk perception as comprehension* there were approximately 1% of missing data which did not affect the results by imputation. For the outcome *COVID- 19 vaccination intention,* a value was available for only 51% of participants, no imputation was done due to a too large uncertainty that would have resulted from that in the model.

Chapter 8: Discussion

This research work aimed to address the overarching goal of determining whether and how to communicate the concept of community immunity to members of the general public who may not yet understand this pillar of infectious disease epidemiology. The COVID-19 pandemic, which began at the end of my doctoral work as I was preparing to run my third and final study, highlighted the crucial importance of this goal. To answer this we had three main objectives: 1) To synthesize existing literature describing the design or evaluation of interventions intended to convey the concept of community immunity, 2) to develop an application incorporating prototype visualization of community immunity and iteratively optimize people's cognitive and emotional responses to it, and 3) to evaluate the effects of the application on risk perception (to individual, family, community and vulnerable people in communities) (primary outcome) and on knowledge, emotions, trust in information and vaccination intentions (secondary outcomes).

In this section, I will first present the synthesis and discussion of the key results of my research, its limitations, the contributions this work made to the literature, and the suggestions for future work. Lastly, I will end with a general conclusion.

8.1 Synthesis and discussion of the key results

My work offers five key results discussed in detail below. First, my thesis amplifies and extends the promise of visualization in communicating about infectious disease epidemiology. Second, it highlights the importance of emotion in vaccine decision making. Third, I evaluated the effects of Herdimm application across different outcomes and found that it improved *risk perception (as comprehension* and *as feelings), knowledge, emotions*, and *vaccination intentions*. Fourth, by incorporating a validated scale of individualism and collectivism, I showed that people with more collectivist orientations are more responsive to messages demonstrating collective benefits of widespread vaccination. Fifth and finally, by evaluating alongside the Herdimm application a number of interventions that had not been previously evaluated head-to-head or at all, I showed that, in the context of an unnamed vaccine-preventable disease, the Herdimm application had better *risk perception as comprehension* (by 'better,' I mean a larger effect on this outcome in the desirable direction) compared to one of the interventions; however, another intervention led to better *knowledge* than the Herdimm application and both of the other interventions led to better *risk perception as feelings* than the Herdimm application. In the context of named diseases (measles and flu), the Herdimm application had better *risk perception as comprehension* compared to two of three interventions and better *knowledge* compared to all three. The Herdimm application also had better outcomes on *emotions*, *trust in information*, and *vaccination intentions* compared to one of the measles interventions.

First, my work confirmed that visualization remains a useful avenue for communicating about infectious disease epidemiology. I added personalization in an effort to increase the user's identification with the avatars, a voice-over to increase learning particularly among people with lower literacy, and a focus on the protection of vulnerable members of a community. In addition to previous research by Betsch and colleagues (Betsch et al., 2013, 2017), other studies have also pointed to the potential advantages of using visualization and videos to convey the concept of community immunity (Alstyne et al., 2018; Nowak et al., 2020). Visualization appears to be a promising medium for conveying what community immunity is and how it works, and by involving users in iterative cycles during the design process, my work showed that it is possible to create a relatively short and simple visualization that conveys a mathematically complex topic. This aligns with previous literature suggesting that visualizations can support people in understanding complex concepts (Hasana & Alifiani, 2019; Luzón & Letón, 2015; Rieber et al., 2004), and that users' involvement in the design process can facilitate an understanding of the information (Breakey et al., 2013).

Secondly, people making decisions about vaccines may be confronted with highly emotional information. Emotions play a crucial role in decision making (Lerner et al., 2015; So et al., 2015), especially when deciding on behalf of loved ones (Jonas et al., 2005b), as is the case when deciding about vaccinating one's children (Gavaruzzi et al., 2021; Zikmund-Fisher et al., 2006). Emotions influence decisions through their effects on risk perception (Betsch et al., 2010), attitudes, and behavioural intentions (Fazio, 1995; Kahneman et al., 1998; Kahneman & Ritov, 1994; Tomljenovic et al., 2020). Despite the clear role of emotions in decision making and the evocation of emotions in much media about vaccines, I found that previous studies frequently did not consider emotions when explaining community immunity (Hakim et al., 2019). My work showed that considering emotion during the design process can help inform the final design of the intervention as well as its evaluation. In keeping with the Affect Heuristic within my integrated conceptual framework, my study explicitly considered emotion, as expressed in verbal feedback and measured with psychophysiological data. Recall that, according to Peters and colleagues (Ellen Peters et al., 2006), affect has four possible functions in health communication and decision making. Affect can directly influence decisions according to a person's subjective sense of the goodness or badness of options; it can function "as a spotlight" to direct a person's attention toward information, which, in turn, shapes their judgments and decisions; it can motivate information processing and behavior; and it can help people trade-off between concepts that are difficult to compare directly. Because our application is designed primarily to convey a complex concept to inform decisions, we focused on affect's function as a spotlight and adapted our application to better provoke emotional reactions to key information, such as the vulnerability of some community members. Attending to data about participants' emotions throughout the design process therefore helped us carefully adapt our application to the way people perceive and use information to make health related or other decisions.

Third, my work evaluated the effects of the Herdimm application on outcomes including *risk perception, knowledge*, *emotions*, and *vaccination intentions*. People's risk perception influences their decision to be vaccinated or not. People often perceive risk based on their impressions of overall disease prevalence and severity (Durham & Casman, 2012; Funk et al., 2010). For example, if risk of infection seems low, small risks of adverse effects from a vaccine seem relatively unimportant and may result in low vaccine uptake. Previous studies have shown that even brief exposure to vaccine-critical websites information can increase people's perceptions of the risks of vaccinations (Betsch et al., 2010; Tustin et al., 2018). My work explored the influence on risk perception of conveying epidemiological evidence about how vaccines work within populations. By presenting epidemiological evidence in a way that allowed people across backgrounds, education levels, and disability statuses to understand it, participants had improved understanding of levels of risk (*risk perception as comprehension*). The Herdimm application also led to improved *knowledge,* which is consistent with other work where web-based intervention improved knowledge and attitudes towards Human Papillomavirus vaccines (M. Kim et al., 2020). In these cognitive outcomes (*risk perception as comprehension*, *knowledge*), the application also improved affective outcomes (*risk perception as feelings, emotions*.) Recall that the *Risk as Feelings* framework describes people's reactions to danger as instinctive and intuitive (Slovic et al., 2004; Slovic & Peters, 2006). For instance, when people have a positive attitude toward an event or a stimulus, they tend to perceive low risk and high benefit associated with it, whereas the opposite happens when they have a negative attitude (Finucane et al., 2000). In my third study, people who were assigned to the Herdimm intervention had higher *risk perception as feelings* and were more likely to indicate high *emotions* like guilt and worry (for example, high agreement with items including, "I am worried about people in my life (family, friends) getting a vaccine preventable disease," and "I would feel guilty if someone in my life (a family member, a friend) got a vaccine preventable disease from me.") This finding is consistent with the previous research where the emotional side of risk perception influenced decision making in the cases of vaccine uptake against influenza (Chapman & Coups, 2006; Weinstein et al., 2007) and COVID-19 (Caserotti et al., 2021). Risk perception also influences vaccination intentions (Schmid et al., 2017). The Herdimm intervention increased *vaccination intentions* across the four diseases studied, which is consistent with other studies (Betsch et al., 2017; Schmid et al., 2017; Vietri et al., 2012). Specifically, studies conducted by Betsch and colleagues (2017) and Vietri and colleagues (2012) showed similar increases in vaccination intentions following communication about community immunity as I observed with the Herdimm application. This suggests that communicating population-level benefits of vaccination may help encourage vaccine uptake, at least in some populations.

Fourth, one of the important results of my work comes from my incorporation of a validated scale of individualism and collectivism (Triandis & Gelfand, 1998) to assess whether a person's orientation towards individualism or collectivism moderated how they responded to the Herdimm application. My findings imply that people with more collectivist orientations were more responsive to the community immunity message than those of individualistic orientations. In contrast, Betsch and colleagues analyzed the effects of Robert Koch intervention across Western (individualist) and Eastern (collectivist) countries and showed that their intervention had larger effects in encouraging vaccination intentions in Western countries than it was in Eastern countries because baseline vaccine uptake was already high in Eastern countries and there was therefore less room for change (Betsch et al., 2017). My work, therefore, builds on these findings to show that even within a Western country like Canada, individuals have different orientations. Some people are more collectivist while others are more individualist, and these individual differences may influence how people respond to public health appeals to protect others.

Fifth and last, my work also contributed evaluations of a number of interventions that had not been previously evaluated and reported in the peer-reviewed literature. Only one of the previously-existing interventions had been evaluated (Betsch et al., 2017), and Canada was not one of its study sites. By conducting head-to-head comparisons of the interventions, I found that the Herdimm application had more desirable results when there was a specific disease under discussion (namely, measles or flu) but two other interventions had more desirable results when addressing the topic of community immunity in the context of an unnamed vaccine-preventable disease. Because my study took place at the height of the COVID-19 pandemic when vaccines were becoming widely available in Canada, it is possible that many study participants mapped "vaccine-preventable disease," to COVID-19. The Robert Koch web-based simulation (Robert Koch institut) led to more favourable outcomes such as *risk perception as feelings*; however, these results were driven by people with higher levels of education. It may be that more educated people respond better to an intervention that allows them to set values for vaccination rate and reproduction number, and see simulations that incorporate movement of humanoid figures. The animated video developed by SBS News in Australia also had some more favourable outcomes. It may be that simply viewing a video without being required to do anything like set values on sliders (as in the Robert Koch intervention) or create avatars (as in the Herdimm intervention) allows people to focus more on the content. This may be especially true in the case of an online randomized controlled trial, in which study participants are recruited from survey panels and incentivized to finish the survey as quickly as possible. Neither the Robert Koch nor the SBS News interventions incorporated any personalization. It may be that the personalization of building an avatar distracted people from the content we were aiming to convey via the Herdimm intervention.

8.2 Limitations

My work had six main limitations. First, the systematic review may have missed relevant evidence. Although I aimed to be meticulous in my search strategy, it is possible that I missed some relevant studies or interventions. In addition, although I did not apply any language restriction when searching databases, my web searches used English keywords, and therefore, I may have missed interventions in other languages. Most of the evaluation data came from studies of interventions that included information about community immunity as a component of an overall intervention. This means that, in most cases, I was unable to isolate the effects of community immunity components.

Second, the Herdimm application's initial development required users to be able to visually perceive presentations on a screen. Building avatars and launching an application also requires a certain level of computer literacy, meaning that the application may not serve people who do not have access to the internet or are uncomfortable or unable to use computers. By the end of my work, we had fully included accessibility measures in the application (e.g., captions for those who may not hear the narration, and descriptive text for those who may not perceive items on a screen or who are accessing the site via a low-bandwidth connection) but I did not test the effects of these strategies and therefore the application may still have accessibility flaws.

Third, for the evaluation of my application, many outcomes were evaluated with ad hoc questions developed specifically for my study due to the lack of validated scales in the context of communication about community immunity. The only validated scale I included was the 5C scale. Effects on the 5C scale factors were weak or nonexistent.

Fourth, in my third aim, I compared the Herdimm application with other potential comparators across four vaccine-preventable diseases. However, there were no other comparators in the context of pertussis. Therefore, I am unable to report how and whether the Herdimm application might perform in comparison to other visualizations in the context of pertussis.

Fifth, my final study recruited participants from internet survey panels (panels of people who have signed up to complete surveys for small incentives) to compare the Herdimm application to a control and to comparator interventions. The differences between the various study arms meant that study participants in different arms had different requirements to complete the study. Namely, participants in the control arms did not need to do anything aside from answering questions. After completing the initial sociodemographic questionnaire and individualism and collectivism scale, participants in the control arms proceeded directly to answer outcome questions. In contrast, those randomly assigned to an intervention arm had to do something in between completing the individualism and collectivism scale, and answering outcome questions. Some participants only had to watch a short video that was embedded directly in the survey; these participants had dropout rates comparable to the control arms. However, participants assigned to the Herdimm application or the Robert Koch intervention had to leave the survey to visit another website, interact with the website, and then return to complete the questionnaire. This likely contributed to the higher dropout rates seen in these study arms. This also adds a potential limitation with respect to intervention fidelity because by simply linking out to the Herdimm and Robert Koch websites and requiring participants to not advance through the survey until an expected time interval had passed, I had no way to know for certain if people visited the Herdimm or Robert Koch websites. In future, although I cannot add such features to external sites (e.g., Robert Koch), it would be useful to consider requiring participants to enter a code that is only given at the end of the Herdimm intervention in order to complete the study. Also, high dropout rates in certain study arms (specifically, Herdimm and Robert Koch) meant that the effects of the interventions in those study arms may be either overestimated or underestimated. Differences were mostly small, but may nonetheless have impacted my findings. When I examined sociodemographic differences between people who did and did not complete the study, the largest difference I observed was among participants who self-identified as white. Participants with this characteristic were more frequent among the group who completed the study (80% among completes vs 62% among incompletes). Identifying as white was also associated with higher knowledge. This means that my observed effects on knowledge may be overestimated, because there were more people with this characteristic associated with higher knowledge in the Herdimm and Robert Koch intervention arms.

Sixth and finally, some identity elements (e.g., some racial and ethnic groups) had frequencies below my threshold for considering the factor individually. This meant, for example, that I do not know the influence of e.g., Black Caribbean identity as a covariate on my outcomes. This may be a limitation if such covariates are influential to my outcomes. However, given that the racial and ethnic groups that we did maintain had little influence as covariates, it is less likely that the collapsed groups would have had substantial influence.

8.3 Contributions my work makes to the literature

My work offers six main contributions to the literature. First, I contributed the first study synthesizing evidence about interventions explaining the concept of community immunity and their effects. Relatively little evidence was available on the effects of communicating the concept of community immunity. My work therefore highlighted the need for such research.

Second, my work highlights that visualization does indeed appear to be a promising medium for conveying complex concepts such as community immunity. The current context of the COVID-19 pandemic shows how public understanding—or, more importantly and alarmingly, misunderstanding—of scientific concepts can shape how members of the public respond to public health communications. Artificially simplified communications may not be effective for helping people understand why they are being asked to disrupt their lives.

Third, my work offers the first such study in the Canadian population. The only previous research effort to evaluate the effects of communicating about community immunity did not include Canada as a study site. Importantly, given that many studies in Canada are done in only one language (typically English), the Herdimm application was developed and tested in both official languages of Canada.

Fourth, my work offers examples of how to make communication about complex concepts like community immunity personally relevant to more people and accessible across levels of education and ability. The personalization in the Herdimm application in which users make avatars representing themselves and those around them included considerable ethnocultural diversity (e.g., options of hijab, turban, diverse skin colours) in response to study participants' comments and my team's awareness of the need to design for inclusivity.

I included a voice-over to increase learning, especially among people with lower levels of education. To make the application accessible, I included full captions and descriptive text, approaches that more communication tools can and should use to facilitate wider access.

Fifth, I designed the Herdimm application explicitly considering emotion as expressed in verbal feedback and measured with psychophysiological data during the final design of the intervention process. Because we know that emotion is crucial for decision-making, this is an important advance in the way the field develops these kinds of interventions.

Sixth and finally, to the best of my knowledge, my study is the first to consider the role of a person's orientation towards individualism and collectivism. My work therefore contributes evidence of how community immunity messages may influence vaccine acceptance differently among people whose orientations are more collectivist versus those who are more individualist. Researchers and practitioners may wish to consider this factor and potentially design tailored communication materials.

In summary, my work is important because it has practical implications regarding how to design health communication materials about complex topics such as community immunity and other concepts that combine individual and population benefits and harms, such as antibiotic resistance and public health interventions during epidemics. My iteratively-developed, emotionally-salient web application with personalized avatars shows promise as a method of conveying the concept of community immunity to a broad range of members of the general public. This application helps people understand their personal role in population health. My work also showed the value of analyzing the role of individualism and collectivism when studying people's responses to public health messaging. Designing communication messages tailored to people's orientations may be a favourable strategy for understanding the interplay between individual-level vaccination behaviour and community-level risk and benefits.

8.4 Suggestions for future work

Based on my dissertation work, I suggest that future research is needed in four areas. First, my study looked at how community immunity communication interventions like

Herdimm might influence individual-level outcomes; e.g., vaccination intentions. An interesting next step would be to see if and whether these interventions influence views about policies such as those being put in place during the COVID-19 pandemic; e.g., vaccine mandates and vaccine passports.

Second, the Herdimm application had high dropout rates since people had to make 9 avatars before viewing a 2-minute video. Future work should consider either making fewer or automatically generated avatars, to see if Herdimm application can equally be effective while lowering study participant burden. Overall, the Herdimm intervention had effects in the desired directions on all outcomes but, in some instances, other interventions (e.g., Robert Koch, SBS News) had even better outcomes. Future work in visualization development may seek to achieve the best of all worlds for people across all levels of education; for example, by combining the user-centredness, understandability, and personalization of the Herdimm application with the ability to set model variables and view a simulation as seen in the Robert Koch intervention.

Third, the Herdimm application showed promise as a method of communicating the relationship between individual behaviour and community health. It offers a potential roadmap for designing health communication materials for complex topics such as community immunity.

Fourth, since our application requires access to the internet and computers or tablets, it would be useful to explore ways to communicate complex concepts like community immunity where there is no internet access or when people are uncomfortable or unable to use computers.

Fifth and finally, because achieving a better understanding of community immunity increases intentions to vaccinate, future work should explore the integration of such visualizations in decision support tools like patient decision aids. Indeed, my application is currently being integrated into a patient decision aid intended to help people make decisions about COVID-19 vaccines for themselves or their children.

Conclusion

This work is about communicating about herd immunity or community immunity, a topic that is even more relevant now than when this dissertation began. Communicating via visualization may help people to understand such complex concepts and facilitate vaccine decision making.

First, my research synthesized knowledge about interventions available to communicate about community immunity. This part of my work showed that, despite the existence of a number of interventions available for conveying the concept of community immunity, little was known about how to make this concept comprehensible to members of the general population. Further, very few interventions had been evaluated for their effectiveness and none of the studies evaluated emotions as an important antecedent of vaccination decisions. Therefore, there was a need to develop an emotionally-salient visualization and evaluate its effectiveness.

The second part of this work was thus initiated to develop an interactive web-based application called “Herdimm” through a user-centered design process. I involved people from diverse backgrounds in an iterative design process, making it possible to create a short and simple visualization that clearly conveys a complex topic. My application showed promise as a method of conveying the concept of community immunity to a broad range of members of the general public, and personalized avatars helped people to understand their personal role in population health.

Lastly, I evaluated the Herdimm application, and found that conveying the concept of community immunity improves risk perception, emotions, knowledge, and influences intentions to receive vaccines. This work is increasingly relevant as countries around the world begin and continue COVID-19 vaccination campaigns.

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Appendices

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