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Covid-19 Modelling Aotearoa

A Summary of Risk Factors for COVID-19 Infection in Aotearoa New Zealand

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Between early-2020 and mid-2023 researchers in Covid-19 Modelling Aotearoa (CMA) compiled information from literature on a range of factors relevant to differential risk of COVID-19 transmission. This was complemented in places with analysis of data from Aotearoa New Zealand in order to contextualise international findings and to place them alongside information about the demographics of Aotearoa. This report provided context around factors that might affect the risk of infection but which were not necessarily (able to be) specifically addressed in mathematical modelling from CMA. Most of this information was collated mid to late 2021. After minor updates to this document at various points it received internal peer review September 2022 and has been revised following that feedback.

Executive Summary

This report provides a literature review of the risk factors for COVID-19 infection, and discusses the implications for Aotearoa New Zealand (NZ). Grounded in a theoretical framework outlined by Cevik and colleagues (2021)[1], we detail how risk of infection is influenced by factors such as the type of environment, the contact patterns of individuals, individual-level and socio-economic factors. Accounting for a vast range of international research undertaken in contexts where COVID-19 has been widespread, we outline factors impacting on transmission risk in NZ, and which populations are likely to be affected. We maintain an explicit focus on risk factors for Māori and Pasifika Peoples. Key findings include:

- Indoor settings carry higher transmission risk than outdoor settings, with this related to ventilation and crowding. Importantly, outdoor settings do still carry some risks, especially in colder weather.
- Public-facing roles, essential work, and shared-work environments all carry higher risk of infection. These roles are often lower paid, have less opportunity to work from home, and are disproportionately composed of workers from marginalised groups in other countries, and Māori and Pasifika Peoples in NZ.
- Different mitigation strategies explain why findings on risk in school environments are mixed. School-age children may carry lower risk of infection, but school re-openings have been shown to drive outbreaks, especially in cases where mitigation strategies are not followed such as mask-wearing.
- Infection risk is higher within households with many close contacts. Household crowding exacerbates risk, as does housing quality such as damp living conditions or indoor pollution. Marginalised groups in the US and UK are over-represented in crowded households of poorer build quality and Māori and Pacific peoples are also over-represented in these types of households in NZ.
- Individuals who are older and/or have comorbid health conditions have increased infection risk. In the NZ context, Māori and Pacific peoples have higher rates of co-and-multi-morbidity.
- Across each of the risk factors considered within the model of risk proposed by Cevik and colleagues[1] such as environment, contact patterns, individual and socioeconomic status, Māori and Pacific peoples face heightened and compounded risk. Mitigation strategies must be tailored towards these populations to achieve equitable public health outcomes.
- There are some caveats and limitations that should be considered with our review. Pathogen characteristics are out of scope for this review (which may be particularly important to consider when multiple variants of the same infectious disease emerge), and the review cannot be considered systematic. Despite this, the review does provide an extensive summary of risk factors for COVID-19 infection in NZ.

1. Introduction

The COVID-19 pandemic has had a profound impact on populations around the world. The combined effects of the direct health impacts from infection, and the public health measures taken to prevent spread continue to have wide-reaching implications, exacerbating pre-existing health inequalities and creating social challenges that will continue to impact communities for many years to come[2,3]. Studying the spread and impacts of the virus necessitates understanding the risk factors involved. Specifically, it is of paramount importance that we fully understand the factors that increase the risk of transmission. With knowledge of which factors contribute to transmission risk, we are better able to identify and care for systemically disadvantaged population groups.

Following the trajectory of the pandemic since its genesis, it has become clear that the ongoing burden of COVID-19 is not evenly distributed within societies[2,3]. Black and Hispanic populations in the US, as well as indigenous populations in other countries[4], have experienced disproportionately high rates of infection from COVID-19[5,6]. Areas of higher deprivation are also associated with high infection rates[4,7].

In order to interrupt this cycle of reinforcing inequalities, we must first understand the factors that contribute to transmission risk and how they interact. Better understanding how COVID-19 is transmitted enables the identification of high-risk environments and activities that contribute to its spread, and facilitates the design of effective preventative measures[1].

This work seeks to provide a detailed summary of the risk factors that are relevant for the context of NZ specifically. Our review is grounded in the theoretical framework developed by Cevik and colleagues (2021)[1] which describes four specific factors that contribute to transmission risk (Figure 1). These factors include the environment, contact patterns of individuals, individual-level factors, and socioeconomic factors. Pathogen-related factors, a growing area of research in the era of multiple COVID-19 variants, are considered out of scope for this population-focused report. Indeed, variant characteristics make little difference to the design and implementation of control measures, which are much more focused on personal and behavioural factors. This report will describe research according to each risk factor in terms of COVID-19 transmission risk, using research carried out from 2020 to 2022. Finally, we describe how the intersecting of these risk factors can compound risk for individuals and communities across NZ.

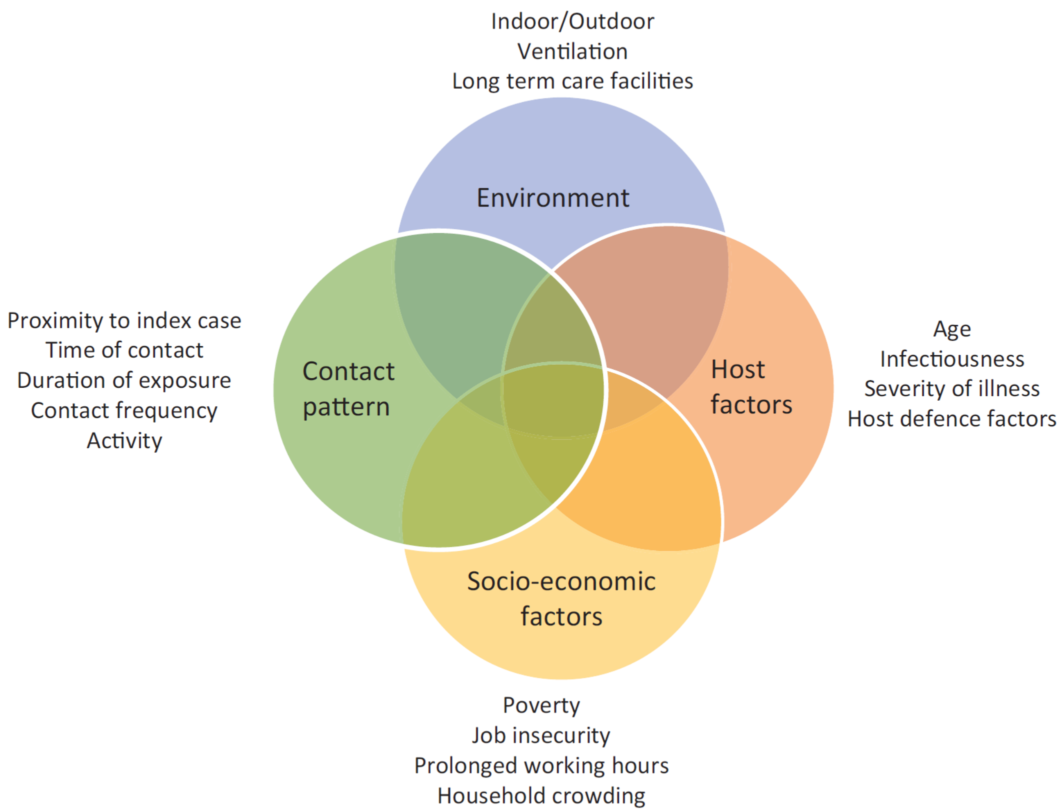

Figure 1. Reproduced from Cevik et al. (2021)[1] - the venn diagram shows the overlapping risk factors of environment, contact pattern, host/individual-level factors, and socio-economic factors.

2. Environment

The environment in which individuals are placed will influence their risk of COVID-19 infection. Overall, outdoor settings have been found to be less risky compared to indoor settings, with a common assertion being that the risk of COVID-19 transmission is roughly 20 times lower outside than indoors[8]. However, the source of some specific estimates are very brief reports of, for instance, 110 cases across Japan[9], and may not be statistically reliable. Systematic reviews do corroborate this finding[9-12], but issues with missing details on outbreaks make it difficult to assess when and where transmission does occur. For example, instances of outdoor outbreaks may occur (e.g. sports games, summer camps, concerts) but transmission is likely to have taken place in enclosed spaces associated within the event, such as shared transport or ancillary indoor socialising. The ease of implementing interventions such as social distancing and mask-wearing is also likely to be an important factor in mitigating the risk of transmission in outdoor contexts[10,13].

2.1. Outdoor settings

Research finds that outdoor settings do carry their own specific risk factors. Crowding, wind speed and direction, and meteorological conditions all play a role in increasing risk[14]. Based on these types of factors, Garcia and colleagues determined a hierarchy of risk for different outdoor contexts[15]. They found that the higher risk contexts include street cafes, busy outdoor markets, and metro/train stations, while walking on busy streets holds comparatively low risk of infection. However, research suggests that the transmission risk associated with outdoor settings is much lower than that associated with indoor settings, with them only becoming somewhat comparable in 'extremely specific meteorological and topographical' conditions[16].

2.1.1. Weather and Seasonality

The seasonality of human respiratory pathogens in temperate regions is well documented[17,18], and will play a role in transmission risk. Research suggests that colder weather can impact climate-dependent components of a host's immune response, thus increasing susceptibility to infection. This risk is further compounded by the enhanced stability of some viruses in cold and dry conditions.[17-19] Each of these factors is likely to affect the spread of COVID-19, with seasonality estimated to account for 40-60% of cases[20]. Importantly, COVID-19 seasonality may be more pronounced at higher latitudes. Seasonality alone is not sufficient to curb COVID-19 transmission, and infectivity and mortality of SARS-CoV-2 are both higher in colder climates[20]. Colder seasons also serve to influence the behavioural patterns of individuals, with people spending more time indoors and at home, work, and school during winter months. The following section details the factors associated with indoor settings that heighten the risk of transmission.

2.2. Indoor Settings

Poor ventilation[21], sanitation[22], and crowded, high density settings[23] are all factors associated with being indoors that have been found to increase transmission risk. Newer, more contagious variants of COVID-19 continue to be highly transmissible in indoor environments[24]. Factors such as ventilation and social distancing play important roles within shared contexts in reducing risk. In winter months, these factors are especially important as ventilation can compromise thermal comfort and energy use[21]. While public transport may serve to carry infection to different areas, transport/vehicles themselves may not be as risky compared to other indoor contexts depending on type of transport and length of exposure duration[25,26]. The following sections discuss the contexts of workplaces, schools, and long-term care facilities specifically, each of which have been found to be key locations where transmission takes place.

2.2.1. Workplaces

Industries where workers have many potential contacts and/or public facing roles, such as retail, tourism, and healthcare, carry a high transmission risk[27-29]. A study of several Asian countries found that healthcare workers (22%), drivers and transport workers (18%), services and sales workers (18%), cleaning and domestic workers (9%), and public safety workers (7%) had the most reported COVID-19 cases within 40 days from the first recorded transmission[30]. The same study found that services and sales workers, drivers, construction labourers, and religious professionals were most at risk in the early stages of an outbreak, with healthcare workers and cleaners becoming more likely to be affected in the later stages[30].

Individuals who are less able to minimise contacts, such as essential workers, face increased risk[31,32]. As outlined by Dingel and Neiman[31] *"managers, educators, and those working in computers, finance, and law are largely able to work from home. Farm, construction, and production workers cannot."* This same pattern is observed in Aotearoa New Zealand, where workers in information technology, financial, and scientific/technical industries also have increased capability to work from home compared to other industries[33]. Evidence is varied in terms of healthcare sectors, which carry the increased risk of essential work as well as increased contacts (and potentially the known infectiousness of contacts), although these workers also tend to have access to high quality Personal Protective Equipment (PPE), testing, and other interventions, and may encounter patients when they are later in the disease course and are less infectious[34].

Other industries may have further risk due to the shared working environments[29], with shared travel and living accommodation being especially risky. Workplaces which have high-density, shared, indoor workspaces, such as call-centres[35], prisons[36], food processing plants[37,38] and manufacturing[39], all carry increased risk of transmission for workers. For environments such as food processing and agricultural work, risk will also be increased by the combined effects of shared transport and living spaces[39], as well as lower temperatures which can increase viral transmission[40,41]. Mirroring the events of many other countries[42], Aotearoa has seen many outbreaks on maritime vessels, which provide an environment where close contacts are difficult to avoid[43].

The risks of infection within workplaces are mainly carried by those who are potentially less well-resourced to mitigate them. The individuals who face the riskier workplace contexts outlined above, especially the reduced opportunity to work from home, are more likely to be paid less and also represent disadvantaged populations[31,32]. Research from the US shows that individuals from these backgrounds are more likely to work in high risk industries such as food processing and agriculture work[5], retail[26,27], and correctional facilities[36]. Individuals from marginalised populations in the US are also more likely to live in households with health sector workers[32]. These same risks are borne similarly by individuals in NZ. Some industries were more protected than others by non-pharmaceutical interventions, with essential workers in retail trade, accommodation, food services, transport, postal services, warehousing, manufacturing, utility services, health care, social assistance, and construction being less able to work from home.

Echoing patterns seen in other countries[31], people in lower-paid jobs in NZ were less likely to be able to work from home[44], while data from the 2020 Household Labour Force Survey (HLFS, 2020) shows that the distribution of workers across different industry sectors in NZ is uneven across ethnicity, such that Māori and Pacific peoples have increased representation in the higher risk, lower-paying occupations. Figure 2 shows how workers in each of the main ethnic groups are split across different industry sectors. Compared to non-Māori/non-Pacific individuals, Māori and Pacific individuals are more likely to work in Manufacturing (1.25X and 2X times for Māori and Pacific respectively) and Transport/Warehousing (1.5X and 2X respectively), both of which are industry sectors with fewer opportunities to work from home. People who are not Māori or Pacific are more likely to work in retail, (which provides limited opportunities to work from home), but also tend to be more likely to work in industries where working from home is possible (e.g. Professional, Science and Technical services, Finance, Information/telecommunications). In terms of age groups, as shown in Figure 3, younger individuals in NZ are much more likely to work in retail, but less likely to work in healthcare, education, and transport industry sectors. Older individuals (aged 60 years or more) are more likely to work in healthcare as well as transport, while less likely to work in accommodation/food services and construction.

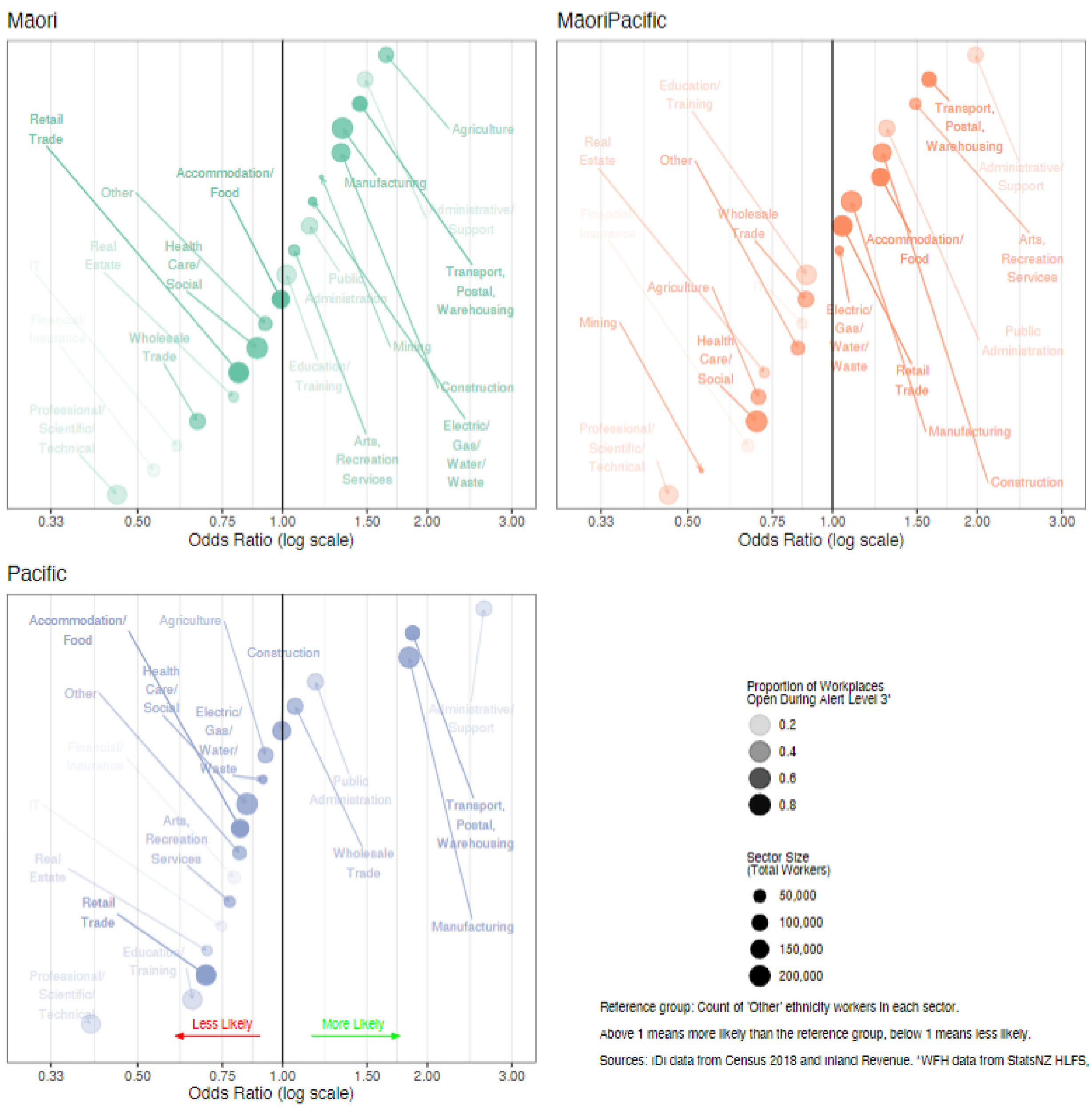

Figure 2. Odds of individuals being employed across different industry sectors (ANZSIC06 classifications) by ethnicity. [Disclaimer: these results are not official statistics. They have been created for research purposes from the Integrated Data Infrastructure (IDI) and which is carefully managed by Stats NZ. For more information about the IDI please visit https://www.stats.govt.nz/integrated-data/.]

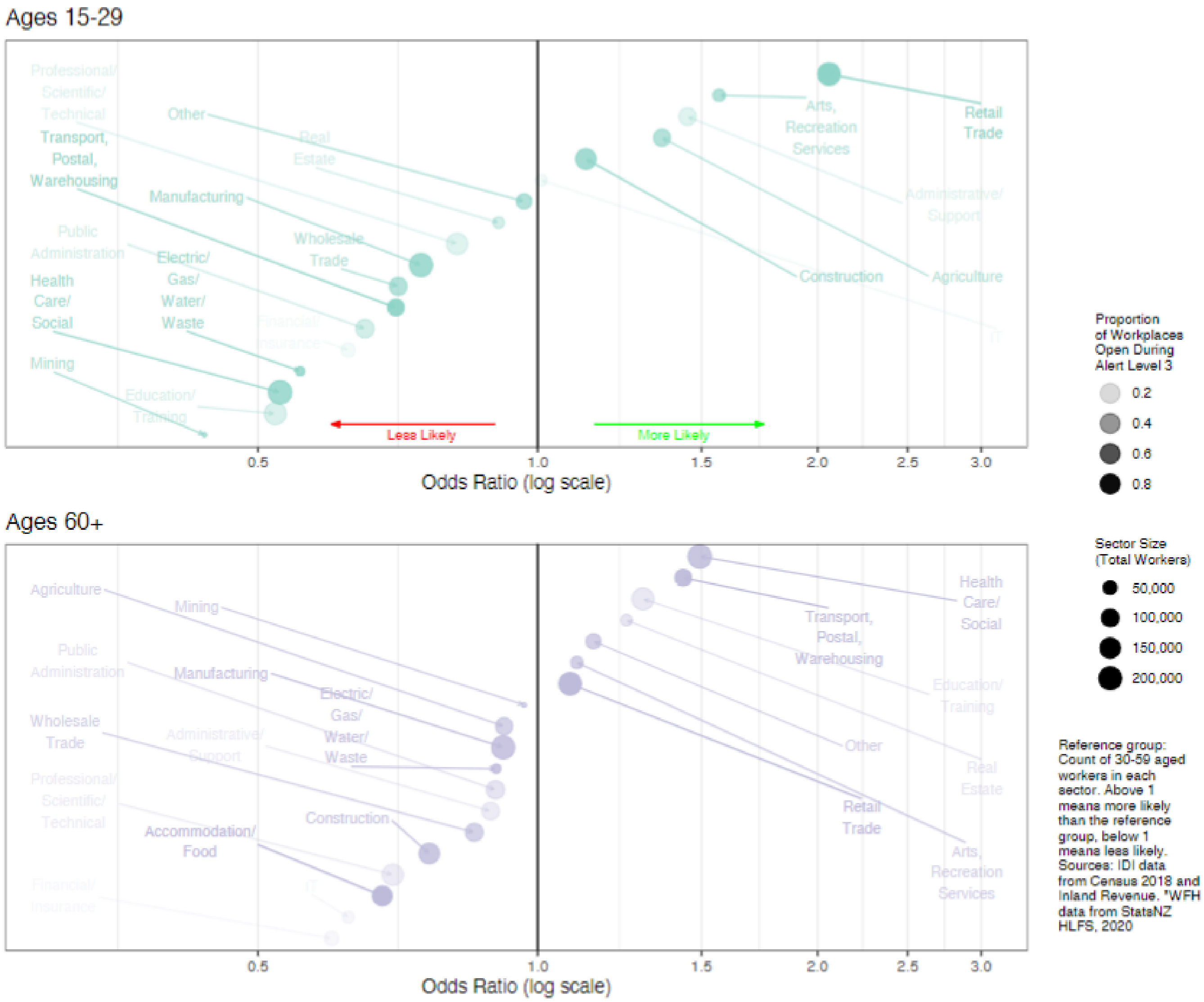

Figure 3. Odds of individuals being employed across different industry sectors (ANZSIC06 classifications) by age band. [Disclaimer: these results are not official statistics. They have been created for research purposes from the Integrated Data Infrastructure (IDI) and which is carefully managed by Stats NZ. For more information about the IDI please visit https://www.stats.govt.nz/integrated-data/.]

2.2.2. Schools

Early research suggested that schools were a relatively low-risk transmission environment for SARS-CoV-2[39,45] however, a wealth of research has emerged to show that school environments have a large role in shaping outbreaks of COVID-19[46-48]. A large-scale study of outbreaks in two Indian states noted a high secondary attack rate amongst children in contact with cases around their own age, suggesting transmission amongst children is common and could be widespread within schools[49]. Analysis of schools in the US[50] and the

UK[51] have shown that the reopening of schools was associated with increased cases, even when controlling for confounding factors such as past infection rates and interventions[47]. It is possible for mitigation strategies to be employed within schools in order to lower the transmission risks in these settings. For example, lower classroom density, reduced recess density, stopping extracurricular programs, ventilation, and mask wearing interventions have the potential to play a large role in mitigating risk of transmission within schools[48,50]. As outlined by Boutzoukas and colleagues[48], universal masking within schools in the US was associated with a 72% decrease in secondary transmission compared to school districts where masking was optional. In a large US study among school districts in the greater Boston area, the lifting of masking requirements was associated with an additional 44.9 Covid-19 cases per 1000 students and staff during the 15 weeks after the statewide masking policy was rescinded[53]. Even if the transmission risk between pupils within schools is comparatively low compared to other contexts, schools are still linked to auxiliary factors that can drive outbreaks, such as crowded public transport, increased connectedness among students[51] and increased mobility for parents[46]. School staff also likely face a heightened infection risk as seen in Aotearoa New Zealand where teachers were the highest-risk occupation group reported during the early-2022 Omicron outbreaks[52]

2.2.3. Long term care facilities and prisons

Long term care facilities such as aged-residential care homes[54,55] and prisons[36] are specific environments where understanding the risks of transmission are particularly important, as these environments are common settings for outbreaks of COVID-19[39]. These environments carry additional risk due to the lack of mobility of residents, the number of unavoidable close contacts, and the potential for additional host vulnerabilities such as older age or co-morbidities for instance[56].

Studies from the US[54,55], Europe[57,58], South America[59], and Asia[60] have shown that aged-residential care facilities are especially high-risk environments for transmission. The risk associated with these types of environments has already been evidenced in NZ, where several outbreaks emerged in aged residential care facilities[43].

Residents of aged-residential care facilities face especially high risks due to the compounding effects of age and underlying health conditions[54]. However, staff can also face increased risk, especially if care home workforce draws disproportionately from populations who are already disproportionately affected in terms of other risk factors. For example, research in the US found that care-home staff were disproportionately comprised of black, female, and low-paid workers, with over 50% at risk of severe COVID-19 illness[61]. The contact shared between staff and residents can pose a significant risk, as younger staff may unknowingly have face-to-face contact with vulnerable residents while asymptomatic[55]. Research from the US has found that smaller facilities tend to be less likely to have outbreaks, although those that do have an outbreak tend to see it spread to a higher proportion of residents within the facility compared to larger facilities[62]. The same research found that the quality rating of nursing homes does not contribute to risk over and beyond the location and size of the facility[62]. This means that nursing homes in the US reflect the disparities seen in the wider population, such that homes located in poorer areas with an increased proportion of residents from underserved population groups face greater risk. Given that less-well-resourced nursing homes are more likely to be located in poorer neighbourhoods, this can explain why other studies have found a negative correlation between ratings of care-home quality and cases[63].

Incarceration facilities are found to be high risk environments for transmission, with prison facilities often being centres of significant outbreaks of COVID-19 among the incarcerated [36,64] as well as prison staff[36,65]. In the US, the case rate among inmates of Federal Bureau of Prisons institutions following the first outbreak in 2020 may have been as high as 5 times that of US adults[66], while case prevalence among prison staff may have been over 3 times that of the US population[65].

For individuals who are incarcerated, there are extremely limited opportunities for social distancing, and risk is exacerbated when facilities are overcrowded and are poorly resourced with, for instance, poor ventilation or inadequate sanitation[1]. In NZ, a considerable number of incarcerated individuals will also have chronic health issues including asthma[67]. The combination of these environmental and individual level factors make prisons a potential hotbed of transmission, while the high number of visitors to these institutions further heightens risk for the incarcerated and their contacts[68].

3. Contact Patterns

3.1. Close Contacts

Friends and whānau of cases typically have the highest risk of transmission, with this influenced by factors such as proximity, duration of exposure and contact frequency[69]. The types of activities carried out in the presence of family and friends may also be closer, leading to heightened risk of transmission compared to contacts with strangers. Evidence shows that transmission risk is increased for spouses[70], while individuals who share the same sleeping space, including co-workers[29,39], are also at increased risk[42]. Household transmission continues to be a key driver of infection with newer more transmissible variants[70], such as Delta[24].

Individuals who are less able to minimise their mobility patterns during the pandemic are at increased risk of infections, and this disproportionately affects individuals from disadvantaged ethnic and socio-economic groups[71]. In the US, research has found that minority ethnic groups are more likely to live in households where someone is unable to to work from home[32]. Individuals who are unable to work from home and are deemed 'essential workers' face higher risk of infection, with Song and colleagues[72] estimating that these workers have a 55% higher likelihood of infection compared to non-essential workers, while room-mates of essential workers have a 38% higher likelihood compared to room-mates of non-essential workers, and co-inhabitants a 17% higher likelihood of infection compared to co-inhabitants of non-essential workers.

Individuals who are more mobile are likely to face increased infection risk. Evidence from the US shows that counties with more mobile inhabitants tended to have a higher number of cases[73]. This may be particularly true for individuals within deprived areas in NZ, which tended to have heightened mobility during the lock-down periods of 2020[44].

Younger individuals tend to have a higher number of contacts[74], and in the context of NZ, younger age groups are more likely to be in both work and education. As shown in Figure 4, for individuals who are aged between 15-29, individuals of 'Other' ethnicity (Pākehā/European or Asian) tend to be more likely to be in work and education, while for older age bands this is more common for individuals who are Māori or both Māori and Pacific.

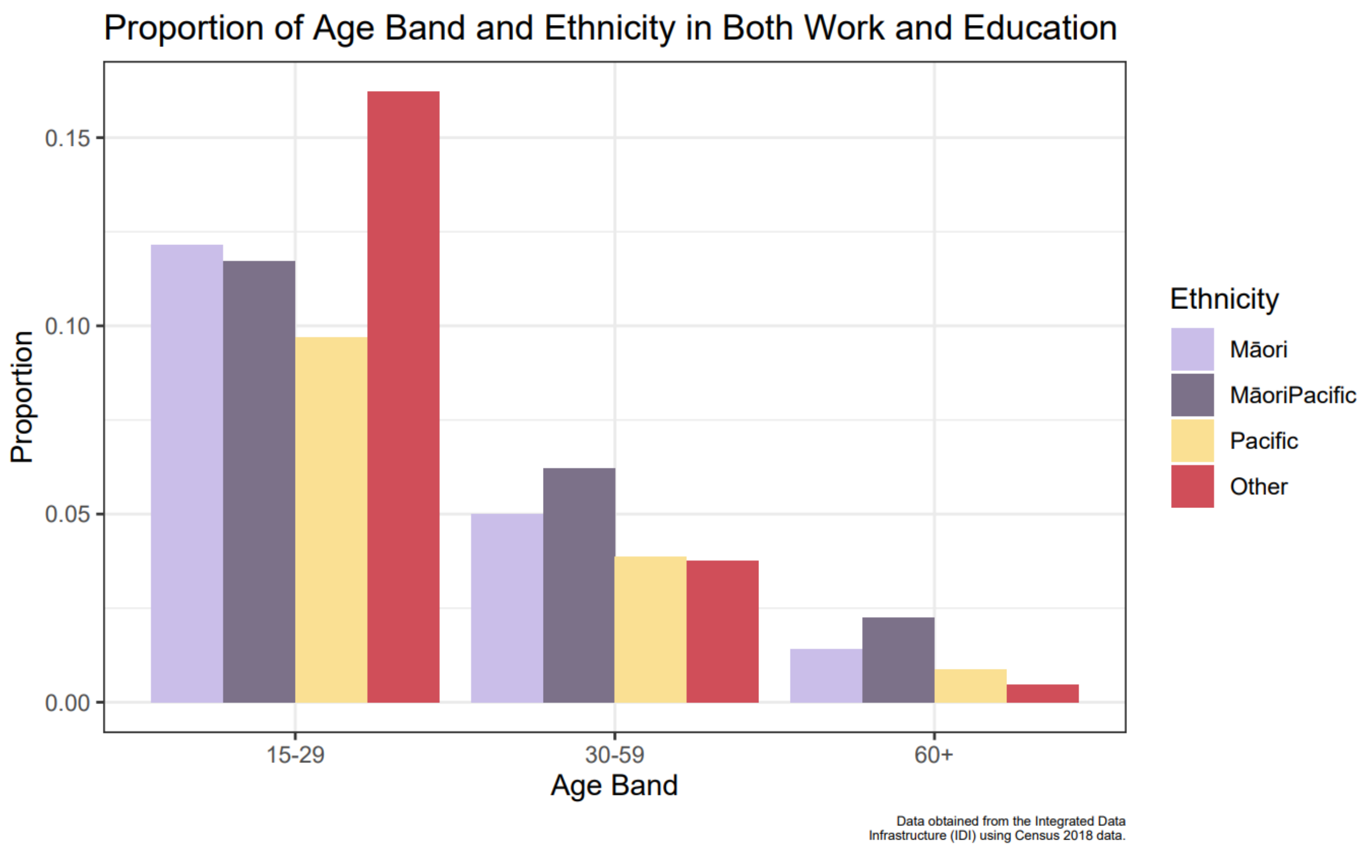

Figure 4. Proportion of individuals who are in both work and education, by age band and ethnicity. Disclaimer: these results are not official statistics. They have been created for research purposes from the Integrated Data Infrastructure (IDI) and which is carefully managed by Stats NZ. [For more information about the IDI please visit https://www.stats.govt.nz/integrated-data/].

3.1.1. Social Gatherings and Events

Social gatherings are commonly found to be high risk contexts for transmission, with these including team sports[24], karaoke[24,75], dancing[75], religious gatherings[39,76], parties[77], and restaurants[75,78]. 'Superspreader' events occurring within these types of context play a distinctly key role in the transmission dynamics of COVID-19[79], with some studies showing that they account for the majority of infections despite comprising a small minority of events[71,75]. Research suggests that the same places can be centres of outbreaks across multiple different waves of infection[78]. In Aotearoa New Zealand, social events, such as weddings, conferences, or religious gatherings, have been common sources for clusters of COVID-19[43].

4. Individual Factors

4.1. Age

Research has shown that older populations face increased risk of infection[80]. When considering all individual factors together, research in the US found that white individuals had higher risk of COVID-19 compared to other ethnic groups, with this mainly attributed to the increased average age of the white population[32]. Research from South Korea found that the risk of infection for the elderly was significantly increased by contact with other age groups, while the elderly themselves pose increased risk for other age groups[81].

Early research found that children, especially those under 10, had much lower rates of COVID-19 than adults, and are more likely to be asymptomatic[76,82,83]. However, it is difficult to assess rates of infection in children as they are less likely to be tested, and work is still needed to elucidate the impact of newer, more transmissible variants on children[83]. More contemporary studies on the Omicron variant suggest that, while severe outcomes following Omicron are less frequent among young children compared to Delta, the incidence rate could be as much as 6-8 times higher[84]. Research in the UK has shown that, as of February 2022, prevalence was highest for children aged between 5-11 years old and lowest for those aged over 70[129].

Studies show that the secondary attack rate is low within households where children are the primary case[82,85,86], although recent research on Omicron has found that cases were more common in households in the UK with children[87]. Studies of earlier variants found that children are more likely to be asymptomatic, and consequently they may also be more likely to be undetected cases. Serological screening of over 11,000 children in Germany found seroprevalence six times higher than would be expected reported case numbers[88]. A similar serological survey from Brazil found little difference between children and adults[4]. Studies show notable differences in the rates of infection amongst children of different ages. While still lower than adult rates, children over 10 years old have been reported to experience higher rates of COVID-19 than those under 10 years old[89], although it is unclear whether this simply reflects higher rates of symptomatic illness in older children. When outbreaks are carefully investigated using both standard and genomic epidemiology, transmission from and to children can clearly be seen[90].

4.2. Health conditions and disability

Individuals with comorbid health conditions face increased risk of infection compared to individuals who do not have any[70]. Comorbidity is usually discussed in the context of severe illness and fatality, however there are several underlying health conditions that may increase the risk of infection. The literature on these is scarce for several reasons: data on patients' health history is rarely collected for cases that test positive but are not hospitalised; additionally, health factors that contribute to infection risk are complex, with the presence of multiple conditions and other risk factors (such as age and behaviour) making it hard to elucidate specific risk-increasing conditions[91].

There are a number of conditions that have been linked to increased risk of contracting COVID-19, most of which affect the immune response in some way[92]. These can include obesity, cardiovascular disease, hypertension, and diabetes[80,91,93-96]. Many of these are linked to over-expression of ACE2, a receptor that acts as an entry point for the SARS-CoV-2 virus[95]. They may also diminish certain immune responses, increasing susceptibility to infection[96]. Individuals who are immunocompromised following cancer treatment will have increased susceptibility whilst also facing increased risk of contact with treatment. Due to the common co-occurrence of the above conditions, both with each other and with factors like age, it is difficult to identify which or how many of these conditions are risk factors in and of themselves, and more research is needed in this area[97]. Research suggests that obesity elevates risk of infection for children as well as adults[82].

Aotearoa has a long history of systemic health inequity, with Māori and Pacific peoples suffering disproportionately from poorer health and well-being outcomes[98,99]. Environmental and socio-economic factors likely contribute to the increased levels of obesity and tobacco consumption observed for Māori and Pacific groups, with the root causes of these issues traced back to structural racism both within healthcare and society at large[98,99]. Māori and Pacific families are more likely to experience high levels of deprivation, including poor housing, which significantly contributes to health inequality. Māori and Pacific individuals also experience significant barriers to access, and poor experiences and outcomes within the healthcare system[100]. Higher rates of co-morbidity and the combination and compounding impacts of risk factors perpetuate disadvantage for Māori and Pacific populations, which, as discussed, heightens the risk of COVID-19 transmission[98].

4.3. Vaccination status

Vaccination provides protection against infectious disease in a number of different ways. Vaccination can reduce the probability of an infection resulting from exposure to a pathogen. It can also reduce the probability of developing symptoms, severe disease, or death when an infection does occur and it can reduce the probability of onward transmission to others from an individual who is vaccinated but infected. Finally vaccination can also reduce the probability of an individual developing longer-term health effects post acute infection (e.g. long Covid). The extent to which each of these protective effects occur depends on an individual's immune history (the timing of any vaccination events, the type(s) of vaccines, and any prior infections) and specific strain or variant of pathogen to which they are exposed, in addition to individual attributes such as age and health status.

The COVID vaccine is an example of a so-called "leaky" vaccine[134] where vaccination reduces, but does not remove, the risk of infection, when exposed to the pathogen[135]. Because vaccination with a leaky vaccine mitigates but does not remove the risk of infection, individuals in sustained close proximity to an infected case or cases - for example sharing a room or prison cell - may have little or no reduction in risk of infection compared with unvaccinated individuals[134]. An implication of this is that people who experience more exposure events, are exposed in environments more conducive to transmission, or who have fewer non-pharmaceutical interventions (NPIs) against transmission (e.g. masks and ventilation) receive only limited benefit from vaccination for avoiding infection, compared with vaccinated individuals who spend more time in safer environments or with more use of NPIs.

Research into NZ's vaccination roll-out found that access to vaccination status was unevenly distributed across geospatial areas, with Māori, Pacific peoples, the elderly (>65 years), and rural residents having poorer access[108]. The Waitangi Tribunal found that the government's decision to not adopt an age adjustment for Māori in the vaccine rollout breached the Treaty principles of active protection and equity[130].

For older variants of SARS-CoV-2 (e.g. those present early on in the rollout of COVID vaccines) there is clear evidence that vaccination reduces risk of infection. In terms of the Alpha variant, research from the Netherlands found that household contacts of vaccinated index cases were less likely to be infected than those who are contacts with unvaccinated index cases[101]. In terms of the Delta variant, vaccinated individuals still have a lower acquisition risk[102]. A study of over a million households in England found that household secondary-attack rates were 40% to 50% lower among households where the index case had been vaccinated (with either the Pfizer or AstraZeneca vaccine) compared to households where the index case was unvaccinated[103].

Evidence suggests that the protection provided by vaccination against infection is reduced for more variants such as Delta[102,106]. Research also suggests that individuals who are not vaccinated disproportionately contribute to infections above and beyond what would be expected given their number of contacts alone[107]. Vaccination against COVID-19 may reduce infectious virus shedding[104], as well as disease severity and duration of symptoms[105], which explains why vaccination can lead to reduced infectiousness.

Since early 2022 the dominant variant of SARS-CoV-2 in circulating in Aotearoa has been the Omicron variant and its sub-lineages. This has substantial immune escape from vaccine protection[131,132] resulting in much lower vaccine effectiveness against infections and transmission, though protection against severe disease and death remain high[133].

5. Socio-economic and Structural factors

Societal context is fundamental to the assessment of risk factors in public health. Socio-economic circumstances create conditions that greatly influence their risk of exposure to and infection with COVID-19. It is important to note that the ongoing consequences of colonisation and systemic racism mean that socio-economic deprivation is felt unevenly across ethnic groups, with Māori and Pacific peoples in particular have lower average income and poorer housing than other ethnic groups[109]. These income and housing disparities have been well documented as contributing factors for high rates of other respiratory illnesses affecting Māori, Pacific, and low-income groups[110-112]. The following sections will outline how these socio-economic factors have been linked to increased transmission risk for COVID-19.

5.1. Socioeconomic deprivation

Past pandemics have shown that the burden of disease is not distributed evenly across wealth brackets, with society's poorest members suffering disproportionately[3]. In NZ, wealth is unevenly distributed by ethnicity, such that on average a European/Pākehā individual will have around 4.8 times as much net worth as an individual who is Māori, 9.2 times as much net worth as an individual who is of the Pacific peoples, and 3 times as much net worth as an individual who is Asian[98]. In addition to pre-existing inequalities and inequities, the consequences of COVID-19 and government responses have caused many New Zealanders to lose income, increasing their relative risk from socio-economic factors[113].

There are several mechanisms that tie income to transmission risk. One such mechanism is poverty's effect on contact patterns and mobility, with increased mobility associated with increased infection risk simply due to increased exposure[7]. Research from the US has shown that high mobility has been associated with both high- and low-income urban areas, but when adverse weather is present, only low-income areas tend to exhibit high mobility[7]. This may suggest that those in higher income areas have more discretion with regard to their mobility. In Aotearoa New Zealand, higher mobility was observed in regions of higher deprivation while COVID-19 restrictions were in place[44]. This reflects the capability of workers in NZ to work from home; workers in managerial, professional, or administrative roles all tend to have a higher number of work hours from home compared to technicians, trade workers, labourers, and machinery operators and drivers[33].

Studies show that poverty can reduce people's capacity to reduce contacts and self-isolate. Lower-income jobs tend to be less adaptable to working from home[31], while increased reliance on income means that poorer individuals may be more likely to continue work while sick[32]. There may also be increased inter-dependence between households for things like childcare and day-to-day necessities[114].

5.2. Housing

A significant proportion of COVID-19 infections can be linked to household transmission, with this in part due to the fact that the household is where the most people spend a large amount of their time[115,116]. The location and quality of housing are both important for shaping the risk of transmission, with poorer areas often seeing higher risk[78,117]. For example, in a study of US households, Ahmad and colleagues[117] found that with each 5% increase in households with poor housing conditions, there was a 50% higher risk of COVID-19 infection. Similarly, a study in Hong Kong identified that 'super-spreading places' are more likely to occur in areas with dense urban renewal and higher median household income-to-rent ratio. The authors suggest that this is due to old buildings with increased crowding, faulty piping, and poorer ventilation[78]. In Aotearoa New Zealand, similar factors are likely to be influential, with the nation's inequalities reflected in the number of people living in inadequate housing and housing insecurity[112]. The specific risk factors associated with housing can be broken down into two key issues: household crowding, and housing quality.

5.2.1. Household Crowding

An obvious risk factor linked to housing is household crowding, with higher occupancy of people living in a space being associated with high transmission risk[115,117]. As outlined previously, individuals sharing the same sleeping space have an increased risk of being infected[42]. Research shows that families in low-income settings[118] and those from minority ethnic backgrounds are more likely to live in multi-generational and crowded households, which contributes to the elevated risk that these groups face[5,115,118]. Household structure likely plays a role in influencing the contact patterns that individuals have. Research has shown that older individuals in middle-income settings, where household crowding is less common, tend to have fewer contacts. In contrast, older individuals in lower-income settings, where larger, multi-generational households are more common, have a higher number of contacts reflecting levels observed for younger age groups[118].

In NZ, experience of household crowding is not distributed evenly across different communities. As illustrated in Figure 5, individuals living in larger household sizes are more likely to identify as Māori or Pacific peoples, and these groups experience the highest levels of household crowding (European/Pākehā the least)[109,111,119]. Household crowding is often an artefact of poverty, and thus will also be most prevalent in Aotearoa's most economically deprived areas[112].

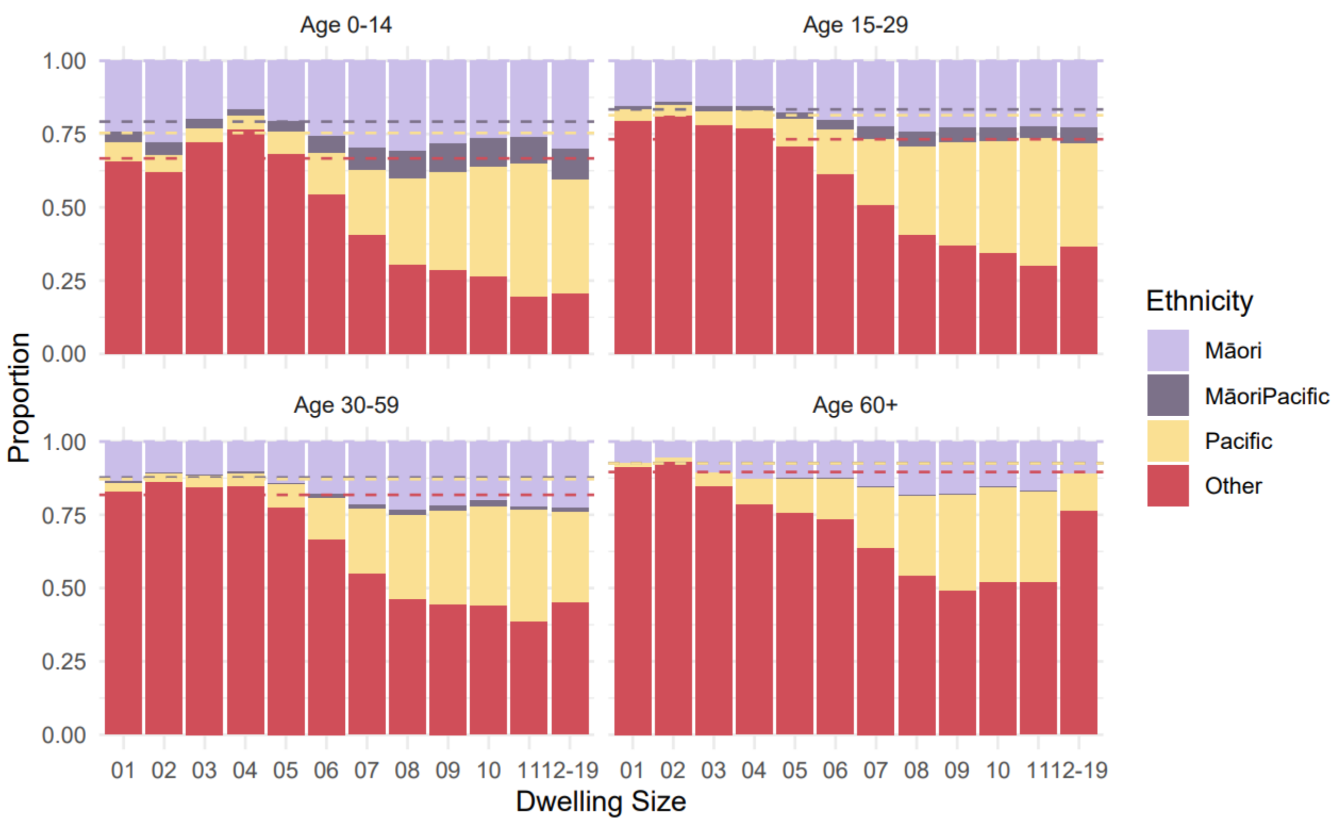

Figure 5. Distribution of household sizes by age and ethnicity. Dashed lines indicate the average proportion overall for each age band and ethnic group. [Disclaimer: these results are not official statistics. They have been created for research purposes from the Integrated Data Infrastructure (IDI) and which is carefully managed by Stats NZ. For more information about the IDI please visit https://www.stats.govt.nz/integrated-data/].

5.2.2. Housing Quality

Another aspect of housing deprivation that may impact COVID-19 transmission is housing quality. This can manifest in poor ventilation, cold and damp living conditions, indoor pollution from smoking or fuels, and inadequate or unaffordable utilities. As mentioned in the first section (Environment), cold environments are linked to increased viral transmission. While dry conditions are likely to be more conducive to transmission than damp or humid ones, dampness in the home has a deleterious effect on health, especially respiratory health, as does air pollution[120-122]. This may not directly affect the risk of viral transmission in the home, although home dampness is a risk factor for acute rheumatic fever (ARF)[123]. ARF can cause rheumatic heart disease, which is a risk factor for severe COVID-19 infection[124].

In Aotearoa New Zealand, research shows that Pacific households have historically had higher rates of damp and cold housing[110]. More recent research has shown that tertiary students are more likely to experience poorer housing quality and energy poverty, especially students with long-term disabilities or who identify as Māori[125]. Young Māori and Pacific children tend to move more often than those from other ethnic groups, and are more likely to move into higher deprivation areas[126,127]. Households who are less able to afford utilities may find it more difficult to ventilate their home, especially in winter time where there are increased demands for thermal comfort within the household[21]. Households with inadequate or unaffordable utilities may be more likely to be interdependent on other households for basic necessities. When household bubbles are connected, the number of potential transmission pathways is increased, with this becoming more extensive when larger households connect[128].

6. Conclusion

The current work provides a review of the risk factors for COVID-19 infection for Aotearoa New Zealand. We draw upon a framework provided by Cevik and colleagues[1] to summarise risk factors across the four overlapping domains of environment, contact pattern, individual factors, and socio-economic factors. With references to previous research across international contexts, we seek to highlight the populations that are most at risk of infection, and the groups that make up the corresponding populations in NZ.

While this review provides an extensive summary of the factors that increase the risk of transmission, there are some caveats and limitations that should also be considered. Firstly, the framework used to structure this report is one of many potential frameworks, and other frameworks may help to elucidate the role of factors, or relationships between factors, that are not discussed presently. For example, the current framework lacks emphasis on pathogen characteristics, which may be important to consider when multiple variants of the same infectious disease emerge (i.e. COVID-19). To date, variant factors have not been a major driver of COVID-19 transmission risk and this aspect was considered out of scope for this review. A second limitation with the work is the fact that it cannot be considered a systematic review of the literature. While efforts were made on the part of the authors to collate a wide range of high-quality studies in the review, database searches and exclusion criteria were not explicitly recorded and quantified. In part, this was the result of the continually changing research landscape as the pandemic unfolded. We strongly recommend a full systematic review be carried out, especially given that many of the studies in the review are now dated, and that the more long-term trajectories and impacts of the COVID-19 pandemic are now known.

With these limitations in mind, the impacts of a pandemic in NZ are highly likely to follow a similar pattern to those observed in other countries. Considering the context of NZ, we find that the risk of being infected with COVID-19 is disproportionately high for Māori and Pacific peoples. To summarise, Māori and Pacific peoples are more likely to be employed in high-risk professions, where wages tend to be lower and the capability to work from home is reduced. Māori and Pacific peoples are more likely to live in larger, more crowded households, have an increased number of close contacts, and be less able to minimise their contacts. Finally, both groups are over-represented in terms of socio-economic deprivation. Lack of economic resources limit the capability of individuals to limit workplace exposure and to access testing. For interventions to successfully reduce overall risks of transmission across the whole of the NZ population, interventions must be tailored to meet the needs of Māori, Pacific peoples, and communities experiencing high levels of deprivation who are disproportionately impacted by systemic inequity.

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