Risk compensation: how vaccination impacts social distancing in an online natural experiment

Krishane Patel[1]

[1] Specialist Consultant; Behavioural Science & Applied Psychology, NatWest Group

Author Note

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The authors made the following contributions. Krishane Patel: Conceptualization, Writing - Original Draft Preparation, Writing - Review & Editing.

Correspondence concerning this article should be addressed to Krishane Patel, 1207, 10 Elvin Gardens, Wembley, HA9 0QG. E-mail: krishane.patel@gmail.com

Abstract

To reduce transmission of COVID-19, public mandates recommended or required minimum physical distancing between individuals, in addition to the use of vaccine rollouts as a public health measure. When individuals are faced with multiple risk reducing behaviours, they may engage in risk compensation. In an online natural experiment, risk compensation was investigated during the COVID-19 pandemic to examine whether vaccination and beliefs in vaccine efficacy reduced physical distancing. Participants completed a distance matching task, where they position avatars of themselves in hypothetical stylized images of everyday scenarios in a 2 (location) x 3 (activity) factorial design. Consistent with risk compensation; the idea that in the presence of multiple risk-reducing behavioural interventions, individuals may choose less stringent behavioural change of one sort, if they benefit of another form of risk-reduction; this study finds that individuals are more willing to stand closer to strangers when fully vaccinated as vaccine beliefs grow. Furthermore, such behaviours do not mitigate when controlling for perceived risk of a COVID-19infection or hospitalisation. A similar finding is observed for vaccine intentions as well as a difference between revealed and stated preferences of risk when comparing across vaccine manufacturers. These results suggest that though vaccines can be effective as a public health measure, the act of being vaccinated may lead to risk compensation that could lead to additional waves from mutations of any such public health crisis.

Keywords: Risk compensation; risky behaviours; COVID-19; vaccination; public policy; judgement and decision-making

Word count: 7606

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1 Introduction

During the COVID-19 pandemic, the governments of the world implemented policies to reduce transmission, to reduce the impact on health systems and vulnerable segments of the population such as the elderly or immunocompromised (Kadambari, Klenerman, & Pollard, 2020; Mikolai, Keenan, & Kulu, 2020; Rout, 2020). Though there were some variations in policy implementation, the central tenant was to delay the impact of the virus until a vaccine programme could be implemented under a mass immunisation approach (Kissler, Tedijanto, Goldstein, Grad, & Lipsitch, 2020; Riel & Wit, 2020). The most common policies to achieve this was through social distancing and mask usage. These policies were based on empirical evidence that demonstrates how presenting new information and by changing circumstances and perceptions of risk can lead to changes in behaviour (Gaube, Lermer, & Fischer, 2019; Wise, Zbozinek, Michelini, Hagan, & Mobbs, 2020). Many governments around the world encouraged individuals to work from home and to reduce social gatherings by closing pubs restaurants and suggesting a physical distance between individuals (often at 2 meters), when interacting with others out of the home. Mask usage became increasingly common throughout the world, much of east Asia the use of face masks was widespread from early in the pandemic, due primarily to public policy, cultural norms and experiences with similar epidemics such as SARS. However, in the United Kingdom for instance, mask use was mandated from 15 June 2020 and primarily in public settings such as public transport or when entering stores.

Much of the public policy space surrounding preventative measures, was enacted to allow time for vaccine programs to implemented. When available countries opted to push for mass immunisation as a public health measure to counter the spread of the SARS-CoV-2 virus (Grabenstein & Nevin, 2006), public health officials believed once available the public would take up the vaccine, however issues around vaccine hesitancy reduced uptake rates (Murphy et al., 2021; Soares et al., 2021; Vergara, Sarmiento, & Lagman, 2021). Issues around vaccine hesitancy led some countries to enforce a vaccine mandate to the general public, such as Austria, Indonesia and Ecuador, with some countries mandating specific populations such as healthcare employees in Australia, Great Britain, France and Germany (Mumcuoglu, Mackos, & Vardon, 2021). Furthermore, some countries mandated the use of a vaccine certificate to confirm vaccination status.

The vaccines were initially shown to be effective in reducing the risk of acquiring a COVID-19 infection or being hospitalised as a result of infection for PfizerBioNTech, Oxford/AstraZeneca, Moderna and Johnson & Johnson's vaccine (Pilishvili et al., 2021; Sadoff et al., 2021; Voysey et al., 2021). However, in the wake of mutant strains of the SARS-CoV-2 virus, the vaccine efficacy was called into question. For example, vaccine efficacy was shown drop in the arrival of the Delta variant, observed initially in India but became the dominant global strain (Agency, 2022). Empirical research demonstrated that vaccinated individuals with the Delta variant showed similar viral loads as unvaccinated individuals (Riemersma et al., 2022). In late 2021 and early 2022, the emergence of the Omnicron variant strain demonstrated a serious issue for the United Kingdom as a third wave of COVID cases threatened the public health system (Burki, 2022). Vaccine efficacy for individuals who completed the original course was estimated to retain 36% effectiveness up to 60 days, dropping to 1% after 180 days (Buchan et al., 2022).

As mutations to the COVID-19 virus reduced the vaccine efficacy rates, this led to pressures on alternative public health measures (including but not limited to social distancing, isolation, contact tracing and mask usage). The interaction of a combination of these measures may have lead people to demonstrate a concept known as risk compensation (Hedlund, 2000; Peltzman, 1975; Underhill, 2013). Risk compensation occurs when an individual changes their behaviour in response to a perceived lowering of risk that occurred through other means. As a result, this new behavior increases the overall risk to the individual and those they feels directly responsible for. There are multiple explanations of risk compensation offered in the literature, for example from an economic perspective safety is balanced against other needs, such as time or happiness (Peltzman, 1975). Other alternative explanations stem from the social amplification of risk framework (SARF) (Kasperson et al., 1988). SARF suggests that risk perception can be amplified or attenuated through signals both processed and transmitted by individuals and social entities. These signals create behavioural responses that can result in secondary impacts or ripples (Kasperson, Webler, Ram, & Sutton, 2022). Risk compensation may arise as a result of competing signals of risk, where one is attenuated and another amplified. As a direct consequence of modulated risk perception, individuals may change their behaviour as a consequence of the modulation of risk.

Risk compensation has been empirically investigated in numerous contexts such as wearing seatbelts (Evans & Graham, 1991; Peltzman, 1975); road lighting (Assum, Bjørnskau, Fosser, & Sagberg, 1999); helmets (Radun, Radun, Esmaeilikia, & Lajunen, 2018; Ruedl, Abart, Ledochowski, Burtscher, & Kopp, 2012); HIV prevention (Eaton & Kalichman, 2007; Marcus et al., 2013; Underhill, 2013) as well as contraception (Shukla, Pullabhotla, & Arends-Kuenning, 2021). Risk compensation has been empirically investigated through a variety of methods, such as laboratory experiments (Phillips, Fyhri, & Sagberg, 2011; Streff & Geller, 1988), natural experiment settings (Assum et al., 1999; Radun et al., 2018); as well as regression analysis (Evans & Graham, 1991; Marlow, Forster, Wardle, & Waller, 2009) and randomised controlled trials (Marcus et al., 2013). The empirical research conducted on risk compensation show that it is not a universal phenomenon, and may be dependent on various contextual factors such as the intervention function and approach and the behaviours being measures.

In the case of risk compensation in the context of COVID-19, the literature has mixed reviews and evidence. Risk compensation has been identified in mask use, for example, Luckman et al. (2021) demonstrated evidence in favour of risk compensation for mask use in social distancing in a lab experiment (Luckman et al., 2021); furthermore this finding was corroborated by a Yan, Bayham, Richter, and Fenichel (2021) who examined Safegraph data showed that people avoid staying at home in states with mask mandates compared to more liberal states. There is some marginal evidence supporting risk compensation from vaccination based on mathematical models, and the effects can be more pronounced if the vaccine efficacy is reduced (Ioannidis, 2021). Furthermore, many researchers have put forward risk compensation as a factor in the waves of the COVID-19 pandemic (Iyengar, Nune, & Botchu, 2022; Mantzari, Rubin, & Marteau, 2020). However empirical results remain mixed, with one study in Taiwan suggesting that vaccinated healthworkers do not engage in risk compensation (Sun et al., 2022), however they operationalise their behaviour with regards to health behaviours (e.g. hand washing). However a study by Buckell et al. (2021), demonstrated evidence of risk compensation across the UK when analysing the Office for National Statistics (ONS) COVID-19 Infection Survey (CIS).

Theoretical understanding of risk are thought be domain and behaviour specific, such that risk in one domain may not be perceived in another. For example, when faced with the same probabilistic outcomes framed as a loss people exhibit risk seeking behaviour, but when framed as a gain show risk-averse behaviour (Kahneman & Tversky, 2013). In the context of COVID-19, the function of vaccinations is to reduce the risk of virility, this reduction is risk may compete against the increased risk as a consequence of the degree with compliance to social distancing. As vaccines do not prevent the individual from carrying the virus, they may still be susceptible to the virus in close proximity.

To investigate this hypothesis, an online natural experiment was ran recruiting individuals from the United States to take part in a distance preference task. In this study, I examine social distancing in a distance preference task, evaluating population differences between vaccine status in conjunction with demographic factors and strength of belief in the vaccine as well as perceived risk. An online distance matching task was used as a behavioural task to assess social distancing judgements, as this was a convenient method being fairly inexpensive to utilise. Furthermore, estimates of distance in digital spaces have been shown to scale as shown in distance tasks in virtual reality and online settings Surtees, Apperly, & Samson (2013). Online tasks demonstrate validity of distance where individuals scale distances as a representative of their field of view in exocentric views, in which the participants are not immersed in the environment but viewing externally Morar, Macredie, & Cribbin (2002). For example Feldstein et al. (2020) found no difference between real and virtual distance judgements, with greater levels of feedback across dimensions increased the accuracy of virtual judgements. Furthermore, these measures are sensitive to detect differences between populations, such as by Welsch, Hecht, Kolar, Witthöft, and Legenbauer (2020) investigated how participants distanced themselves in the context of interpersonal distancing using online avatars.

This study aims to investigate the following pre-registered hypothesis in reference to risk compensation as a consequence of the COVID-19 vaccines:

H_1: Vaccinated individuals will be willing to position themselves closer to others in social situations.

H_{1a} & H_{1b}: It is expected that partially vaccinated (H_{1a}) and fully vaccinated (H_{1b}) choose shorter distance than those who were not yet vaccinated.

H_{1c}: This paper also explore differences between partially and fully vaccinated individuals, where it is expected that not to observe any difference partially or fully vaccinated social distancing across trials.

H_2: Fully vaccinated individuals with strong beliefs of vaccine efficacy will social distance the least.

H_3 & H_4: There is no change in social distancing when controlling for the perceived risk of COVID-19 or risk of hospitalisation (respectively).

H_5: Furthermore, location may affect risk compensation behaviours, where individuals will position themselves further from others when indoors as compared to outdoors.

H_6: Unvaccinated individuals with a vaccine appointment are more likely to position themselves closer to others in social situations than unvaccinated individuals without an appointment (H_{6a}) but show no difference compared to vaccinated individuals (H_{6b}).

2 Method

2.1 Participants and Exclusions

A total of 760 participants were recruited from Prolific (www.Prolific.co.uk) in July 2021, completing the experiment on the Qualtrics platform (www.Qualtrics.com). Participants were paid 0.70c to complete the experiment (at a rate of $8.40/hour). Inclusion criteria were as follows:

- Citizen of the United States
- Over the age of 18
- Prolific user
- Normal or corrected-to-normal vision

Using vaccination uptake data from the Centre for Disease Control (Centre for Disease Control, 2021), it was expexted that around 55.3% of participants would have recieved at least one vaccine dose, and approximately 44% would be fully vaccinated. Based on the above assumptions, it was estimated that the sample would contain approximately 340 unvaccinated individuals, 86 partially vaccinated individuals and 334 fully vaccinated individuals. Participants were asked to self-report theirvaccine status as no pre-screening criteria existed to stratify on Prolific at the time of data collection. Amongst the sample population, 61 self reported as being unvaccinated, 178 as partially vaccinated and 517 as fully vaccinated, this distribution was statistically significantly different from what the CDC reported, $\chi(2) = 92.86$, p $<$ .001.

Monte Carlo simulations were ran, using 1000 trials, to calculate statistical power for recovered effect sizes, assuming the following parameters: fully vaccinated individuals socially distance on average 1.75m (SD = 1.0m), partially vaccinated distance on average 1.88m (SD = 1.0m) with unvaccinated individuals distancing 2.0m (SD = 1.0m), which

Table 1

Breakdown of the observed and expected distributions of different vaccine states in sample population

	Expected		Observed	
Category	Percent (%)	Size (N)	Percent (%)	Size (N)
Unvaccinated	44.74	340	0.24	180
Partially vaccinated	11.32	86	0.08	62
Fully vaccinated	43.95	334	0.68	518

would translate to an anticipated difference of 0.25 standardized units between fully vaccinated and unvaccinated individuals. For the expected distribution of vaccine statuses the simulation obtained a mean effect size $\eta^2 = 0.02$ with statistical power of 82.70%; however with the same assumptions, the observed distribution of vaccine statuses demonstrated a mean effect size of $\eta^2 = 0.01$ and a statistical power of 73.60%. Estimates of effect sizes and statistical power were calculated using the *effectsize* (Ben-Shachar, Lüdecke, & Makowski, 2020) and the *pwr* packages (Champely, 2020).

2.2 Procedure

The primary task participants completed was a social distancing task using a subset of trials from Luckman et al. (2021). This study differs from Luckman et al. (2021) by the following parameters, only the non-masked stranger trials are used, and participants are not informed of the stranger's vaccination status. Furthermore, as this is a natural experiment, participants are also not randomized to their given variable of interest, vaccine status.

Participants placed an avatar of themselves to indicate the closest distance they would be willing to position themselves from another person (described as a stranger) in six different scenarios. These scenarios differed in terms of their location (inside or outside) and in the activity taking place (sitting, walking or standing). Each participant saw all combinations of the 2 (location) x 3 (activity) variations but in a random order to eliminate order effects, with each scenario being presented as a separate trial, with a written description and stylized image for each unique setting. Participants indicated on the image the closest they would be willing to sit, stand or walk to the stranger in each respective scenario. A validation item was implemented by asking participants the purpose of the distance matching task, participants who selected any other response than "the closest they would be willing to sit, stand or walk to the other person" was considered incorrect, these participants were removed from the main analysis.

In each scenario participants were shown an image of the activity and location, with a stranger positioned in a unique setting. As the participant moved their mouse over the image, a grey figure representing the participant would appear in the scene and could be placed in the setting. When the participant clicked on the image, a green box would appear indicating their chosen social distancing preference which was submitted by clicking the 'Next' arrow button. The avatar could be repositioned by clicking on the previous selected box and then clicking elsewhere. In each trial, there were 17 different locations in which the avatar could be placed, during the instructions and prior to the first scenario, participants were informed that the figures represented adults of approximately 1.7m in height. Based on the 17 available positions and the scaling of the avatars, each position mapped to distances roughly between 0 and 4m in 0.25m intervals, however participants were not informed of these units.

After participants complete the distance preference task, they are asked to answer a short survey to understand more about participants (demographic) as well as their vaccine status, and beliefs about the vaccines and COVID-19 virus. Ethical approval for this study was granted by the University of Warwick's Decision Research at Warwick committee (HSSREC: 75/20-21).

2.3 Measures

The primary outcome measure is closest individuals would be willing to socially distance themselves from a stranger in the above six scenarios. In addition, data is collected about participant's current vaccine status (fully, partially or unvaccinated), their belief of the

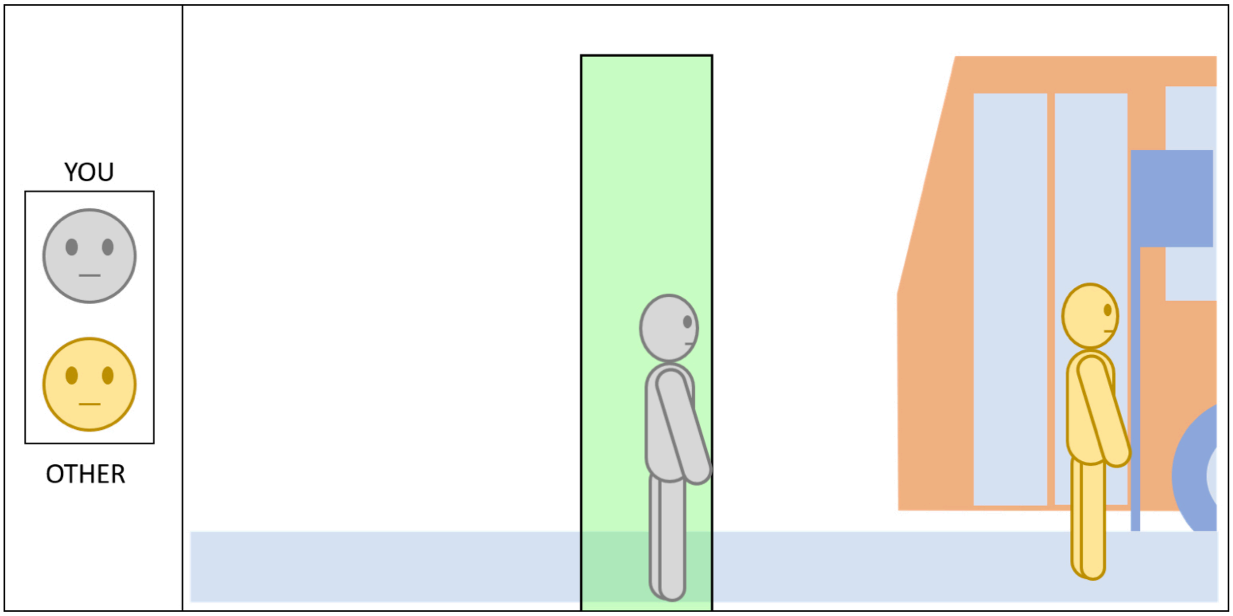

Figure 1. Trial screenshot showing how a participants avatar selects where to position their avatar (grey) by selecting the different green segments in the image depicted. There are 17 different positions participants can select themselves, the current selected position was at 1.8 metres.

vaccine's protective and preventative effects, as well as data on their belief of acquiring a COVID-19 infection as well as hospitalisation as a result of a COVID-19 infection. Furthermore, additional data is also collected on demographic information such as age, gender, state residence, employment status and whether they work in the healthcare setting. Participants are asked to provide subjective judgements of vaccine status distributions (out of 10 people how many are unvaccinated, partially and fully vaccinated). Further data on unvaccinated individuals s also collected on vaccine intention and any upcoming vaccine appointments.

2.4 Analysis

This experiment tested how receiving a COVID-19 vaccine and the belief in the vaccine's protective characteristics, as well as the location of an encounter (inside or outside) might affect the distance people would keep from a stranger for three different activities (standing, sitting and walking). These activities were selected as representative of situations individuals would likely encounter with a stranger. Mixed effects models were fitted to evaluate social distancing across different activities, however there are some additional non pre-registered speculations.

The analytical model was modified due to overfitting of the random-effects, as a result, activity and location were only entered as fixed-effects as there are only one trial for each combination of activity with location. To allow for interpretability, vaccine belief was centred. The model specification used for the main analysis is as follows:

$$Distance_{i,j} = Control_i + Status_i * Belief_i + Location_{i,j} * Activity_{i,j} + (1|subjID_j) + \epsilon_i + \lambda_j$$
$$\epsilon_i \sim N(\mu_1, \sigma_1),\ \lambda_j \sim N(\mu_2, \sigma_2)$$

Where Control is a vector of control variables including age, sex, state residence, employment status, healthcare worker status. Status denotes a self reported variable of whether the individual has received no vaccinations (unvaccinated), one of two vaccine dosages (partially vaccinated), one of one alternatively two of two vaccine dosages (fully vaccinated). Belief denotes the computed aggregate belief score regarding the protection of catching and spreading COVID-19, these are then computed to a single score by averaging across both vectors. Location and Activity denote the trial contexts, in a 2 x 3 factorial design. Data is available on the OSF website (https://osf.io/dv2az).

3 Results

3.1 Sample breakdown

760 participants were recruited from the Prolific platform on the 3rd and 4th July 2021. In line with the preregistered criteria, 92 participants were excluded from the analysis for failing the check question (removal of these participants does not impact the overall results). The final sample consisted of 668 (316 Females; 47.31%; M_{age} = 34.29, SD_{age} = 12.46). A more in-depth detail and breakdown of the sample population is provided in Table 2.

To investigate risk compensation, the distance individuals position themselves relative to the stranger is understood as the minimum they would be willing to socially distance, as measured in meters (in discrete 0.25m units). This study examines how social distancing is affected by whether an individual is vaccinated, and the degree to which they believe in the COVID-19 vaccines, a primary function of risk compensation (Hedlund, 2000).

Table 2

Demographic breakdown of sample population across each vaccine status.

	Full (N = 461)	Partial (N = 47)	Unvaccinated (N = 160)
Age			
Mean (SD)	34.73 (13.27)	32.24 (10.42)	33.64 (10.47)
Missing	12 (2.17%)	1 (2.13%)	1 (0.62%)
Sex			
Male	224 (48.59%)	28 (59.57%)	88 (55.00%)
Female	227 (49.24%)	18 (38.30%)	71 (44.38%)
Missing	10 (2.17%)	1 (2.13%)	1 (0.62%)
Ethnicity			
American Indian or Alaska Native	4 (0.87%)	0 (0.00%)	4 (2.50%)
Asian	107 (23.21%)	7 (14.89%)	5 (3.12%)
Black or African American	32 (6.94%)	10 (21.28%)	40 (25.00%)
Native Hawaiian or Pacific Islander	0 (0.00%)	0 (0.00%)	0 (0.00%)
White	291 (63.12%)	29 (61.70%)	94 (58.75%)
Other	23 (4.99%)	1 (2.13%)	13 (8.12%)
I prefer not to answer	4 (0.87%)	0 (0.00%)	4 (2.50%)
Employment			
Employed	272 (59.00%)	37 (78.72%)	104 (65.00%)
No employment reported	179 (38.83%)	9 (19.15%)	50 (31.25%)
Missing	10 (2.17%)	1 (2.13%)	6 (3.75%)
Healthcare worker status			
Healthcare worker	48 (10.41%)	5 (10.64%)	15 (9.38%)
Non healthcare worker	408 (88.50%)	42 (89.36%)	141 (88.12%)
Missing	5 (2.17%)	0 (2.13%)	4 (3.75%)

3.2 Location and activity

As preregistered, a mixed-effect linear model was conducted using the *afex* package (Singmann, Bolker, Westfall, Aust, & Ben-Shachar, 2022) to evaluate the extent to which people socially distanced across different activities and locations. There was a significant effect of location (F(5, 559) = 3.05, p = 0.01), where people are more more willing to social distance indoors (M = 1.79m, SE = 0.10m) than outside (M = 1.71m, SE = 0.10m) regardless of activity, demonstrating evidence in favour of H_5.

Furthermore differences between activities were explored by comparing sitting, standing and walking using pairwise comparisons. In accordance with the literature, this study seeks to determine differences between sitting, standing and walking replicating the qualitative trends observed by Luckman et al. (2021), where individuals show a preference for socially distance the most when sitting, socilly distance less when walking than sitting, and finally willing to socially distance the least when standing. In this model, there is a significant effect of activity (F(1, 559) = 2.64, p = 0.105), showing that individuals indeed would prefer to position themselves significantly further when sitting (M = 2.09m, SE = 0.11m) as opposed to standing (M = 1.47m, SE = 0.11m) or walking (M = 1.69m, SE = 0.11m) next to a stranger, t(3100) = 16.32, p < .001. Pairwise comparisons revealed significant differences between sitting compared to standing or walking (t(3099 = 16.32, p < .001). Furthermore, this model found that individuals would socially distance more for walking than they would for standing (t(3099) = -6.20, p < .001). These results are displayed more clearly in Figure 2. These effects are consistent with Luckman et al. (2021). It is likely that such differences may related to beliefs around tasks, where sitting next to a stranger is likely a longer interaction than standing which is a longer interaction than walking.

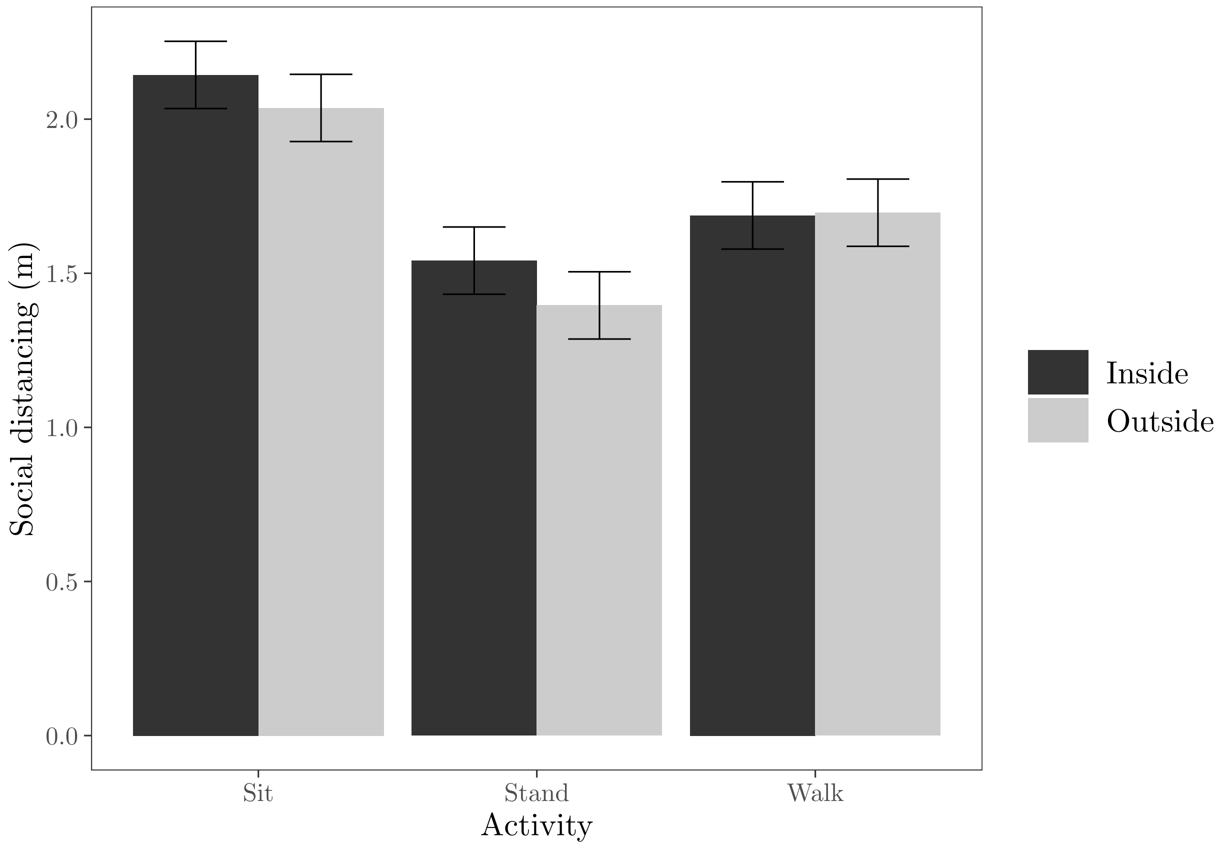

Figure 2. Bar graph showing how mean social distancing (metres) was greatest for sitting, followed by standing and walking, these effects were observed for both inside and outside locations (note: Error bars reflecting SEM).

3.3 Vaccine status and vaccine belief

This model also investigated the effects of vaccine status on social distancing, as well as the moderating effect of vaccine belief. The model demonstrated no effect of vaccine status (F(2, 559) = 0.11, $p = 0.894$), with no significant difference between the average distancing of fully vaccinated (M = 1.69m, SE = 0.14m), partially vaccinated individuals (M = 1.77m, SE = 0.20m) and unvaccinated individuals (M = 1.70m, SE = 0.15m). These results do not support H_{1a} or H_{1b}, as fully vaccinated, partially vaccinated and unvaccinated individuals all socially distance to similar extent.

When evaluating the effect of vaccine status and vaccine belief, the model demonstrates a significant interaction (F(1, 3110) = 35.25, $p < .001$). The model shows

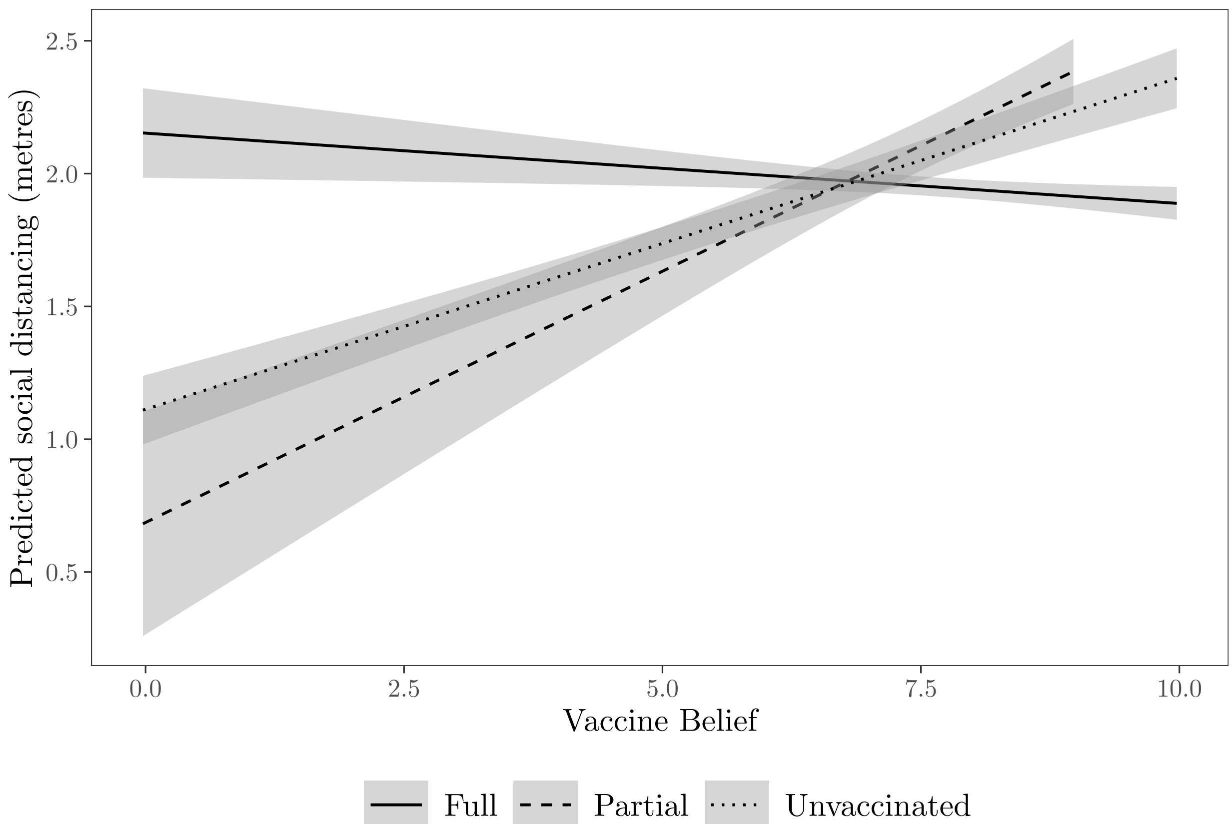

Figure 3. Line graph showing how when vaccine belief increases, unvaccinated and partially vaccinated individuals social distance further, however fully vaccinated individuals reduce social distancing as their belief grows stronger (*note: Error bars reflect S.E.M*)

that belief in COVID-19 vaccines efficacy moderates the effect of social distance in a significant interaction between vaccine status and belief in vaccine (F(1, 3110) = 35.25, $p <$ .001). The results show a negative association between fully vaccinated individuals and vaccine belief where fully vaccinated participants reduced socially distance less by -0.030m for each unit increase in vaccine belief. However, partially vaccinated increase distancing by 0.120m and unvaccinated distance further by 0.102m. Pairwise comparisons of vaccinated against unvaccinated, revealed significant differences (t (651) = -0.13, $p =$ 0.002), this evidence supports hypothesis H_2.

To highlight such differences a linear plot of vaccine belief against predicted social distancing (across vaccine status) is plotted in Figure 3. Based on the model, a fully vaccinated individual with weak beliefs is estimated to stand 2.15m away (95% CI: 1.98m; 2.32m). Partially and unvaccinated individuals with weak beliefs stand closer, with an partially vaccinated individual is estimated to stand considerably closer, at around 0.68m (95% CI: 0.26m; 1.10m), and an unvaccinated individual is estimated to stand at 1.11m (95% CI: 0.98m; 1.24m). However, when estimated social distancing for individuals with the strongest beliefs in the vaccine a fully vaccinated individual is estimated to stand at 1.89m away (95% CI: 1.83m; 1.95m), where partially and unvaccinated individuals stand further away, with an partially vaccinated individual is estimated to stand at 2.38m (95% CI: 2.26m; 2.51m), and an unvaccinated individual is estimated to stand at 2.36m (95% CI: 2.25m; 2.47m).

The population differences may infer different sub-populations where those who hold strong belief in vaccine efficacy compared to those who hold weak beliefs in the vaccine. For fully vaccinated individuals these may indicate population of those who received the vaccine for intentional reasons if they hold high beliefs, whilst opting for the vaccine to return to normalcy for weak to medium beliefs, which could explain the negative association of belief and distancing. However for partially vaccinated who hold strong beliefs may perceive risks of COVID-19 more saliently as their treatment course is not complete and is due for completion with the next 3-4 weeks. Partially vaccinated who hold weak to moderate beliefs may also be opting for vaccinations to return to normalcy and may have held weak or even no intention to get vaccinated. Unvaccinated individuals who hold strong beliefs in vaccine efficacy may also show a high intentions to get vaccinated, which may not be said for those with weak to moderate beliefs, who hold no intention to get vaccinated.

3.4 Vaccine status, vaccine belief and COVID-19 ‘risk beliefs

Initial exploration of subjective risk of acquiring COVID-19 was shown to be non-normally distributed (skewness = 2.00; kurtosis = 8.11) as was subjective risk of hospitalization from

COVID-19 (skewness = 1.81; kurtosis = 5.66). Logarithmic transformations were conducted which substantially reduced the skewness for subjective risk of acquiring COVID-19 (skewness = -0.42; kurtosis = 2.61) as was subjective risk of hospitalization from COVID-19 (skewness = -0.02; kurtosis = 2.01).

To investigate H_3, two additional models were ran which included perceived risk of acquiring a COVID-19 infection, and the perceived risk of hospitalization from acquiring a COVID-19 infection. Initial examination of these variables revealed a significant medium-sized correlation (r = 0.43, $p < .001$), therefore these factors were entered separately into two distinct models to account for multicollinearity. In addition, the models included a fixed-effects factor of a previous COVID-19 infection was a boolean variable (where 1 denoted known or suspected cases; 0 denoting no infection or was not suspected).

This model replicates the effect of location * activity interaction (F(2, 2930) = 5.25, $p = 0.005$). There is no effect of previous COVID infections increasing social distancing (F(1, 526) = 1.39, $p = 0.238$), suggesting that any previous cases of COVID-19 does not increase social distancing.

There is a significant effect of perceived risk of a COVID-19 infection (F(1, 526) = 7.07, $p = 0.008$), suggesting that there is a positive association between the percentage change in belief of acquiring a COVID-19 infection and the degree to which individuals are willing to socially distance. In this model, the interaction for vaccine status and vaccine belief is still significant identifying that the effect of risk compensation is not reduced when controlling for perceived risk of COVID-19 (F(2, 526) = 4.17, $p = 0.016$). Comparisons of slopes across groups demonstrated a significant difference between Fully Vaccinated and Unvaccinated individuals (β = -0.10, $p = 0.05$), replicating the effects observed in the previous model as shown in Figure 4. Estimated distancing in this model would predict that a fully vaccinated individual with weak beliefs would socially distance at around 2.17m away (95% CI: 2.00m; 2.34m), whilst an unvaccinated individual with weak beliefs is estimated to stand at 1.20m away (95% CI: 1.06m; 1.33m). However when estimating

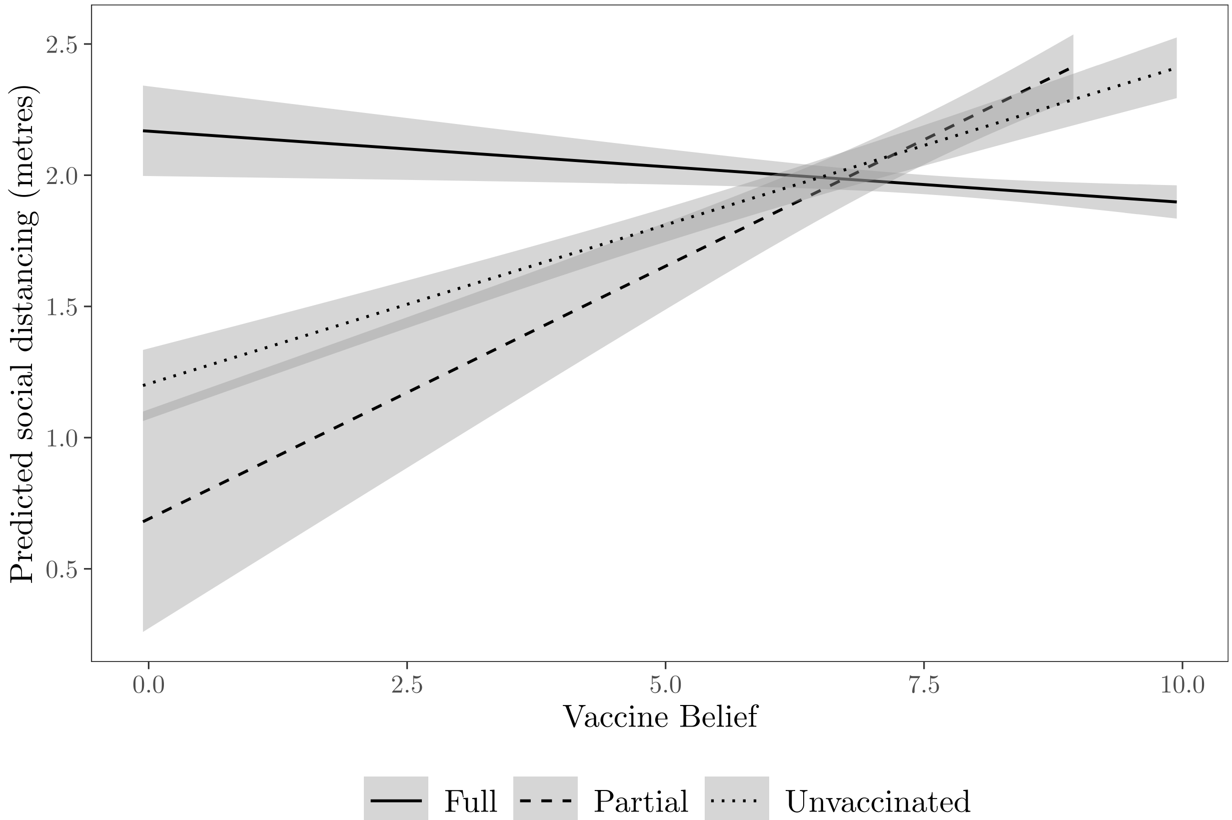

Figure 4. Line graph demonstrating how when vaccine belief increases, unvaccinated and partially vaccinated individuals social distance further, however fully vaccinated individuals reduce social distancing as their belief grows stronger, even when controlling for risk beliefs of a COVID-19 infection (*note: Error bars reflect S.E.M*).

social distancing for strong vaccine beliefs, fully vaccinated individual would socially distance at around 1.90m away (95% CI: 1.83m; 1.96m), whilst an unvaccinated individual with strong beliefs is estimated to stand at 2.41m away (95% CI: 2.29m; 2.52m).

3.5 Vaccine status, vaccine belief and hospitalisation risk

The third model evaluates the risk compensation effect whilst controlling for the percieved risk of hospitalisation from a COVID-19 infection and COVID-19 previous infections. This model replicates the effect of location and activity interaction ($F(2, 2930) = 5.25$, $p = 0.005$). The model does not demonstrate observe any effect of previous COVID infections increasing social distancing ($F(1, 526) = 0.50$, $p = 0.481$), suggesting that any previous cases of COVID-19 does not increase social distancing.

The results do highlight that individuals are more likely to socially distance if they believe they are at risk of hospitalisation if they acquire a COVID-19 infection (F(1, 526) = 16.91, p < .001). This would suggest that as an individuals belief of hospitalization increases the degree to which they socially distance increases by 0.130m for each percentage increase in strength of belief for hospitalisation from COVID-19. The model exhibits however a significant interaction of vaccine status and vaccine belief (F(2, 526) = 4.10, p = 0.017). Comparisons of slopes across groups demonstrated a significant difference between Fully Vaccinated and Unvaccinated individuals (β = -0.11, p = 0.02), replicating the effects observed in the previous model. This is best demonstrated in Figure 5.

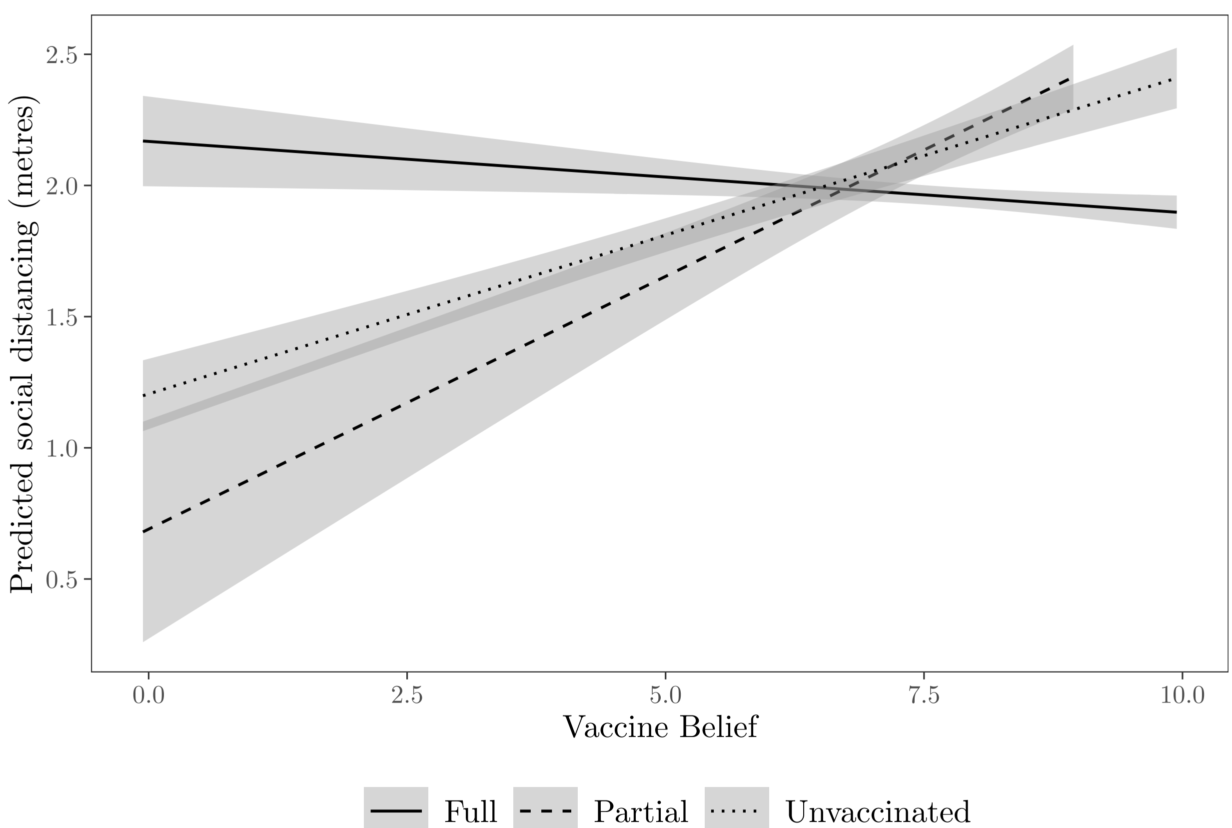

Figure 5. Line graph showing how when vaccine belief increases, unvaccinated and partially vaccinated individuals social distance further, however fully vaccinated individuals reduce social distancing as their belief grows stronger, even when controlling for risk beliefs of being hospitalised from a COVID-19 infection (*note: Error bars reflect S.E.M*).

3.6 Exploratory Analysis

3.6.1 Regressing vaccine status & social distancing on vaccine belief. To explore possible explanations of how vaccine beliefs influence social distancing across vaccine states, a fixed-effects linear regression was conducted, as specified below regressing vaccine status (interacted with averaged social distancing across all trials) on vaccine beliefs, with a vector of control variables. To correct for heteroskedasticity, White's robust standard errors are computed using the vcovHC function of the *sandwich* package (Zeileis, 2006).

$$Belief_i = Control_i + Status_i * Distance_i + \epsilon_i$$
$$\epsilon_i \sim N(\mu, \sigma)$$

The linear fixed-effects model demonstrates population differences vaccine belief, unvaccinated individuals were shown to hold significantly weaker beliefs than fully vaccinated individuals (β = 0.55, p < .001); partially vaccinated were also shown to hold significantly weaker belifs than fully vaccinated individuals (β = 0.83, p = 0.067). Fully vaccinated individuals were shown strongest belief in the vaccine (M = 7.20; SE = 0.21); followed by partially vaccinated individuald (M = 7.03; SE = 0.36) and finally unvaccinated individuals (M = 5.20; SE = 0.24). A post-hoc contrast demonstrated that partially vaccinated individuals hold stronger beliefs than weaker vaccinated individuals (β = 1.83, p < .001). These results describe population differences in beliefs of vaccine efficacy which may play a further role in how vaccine beliefs influence risk compensatory behaviours. As these are population differences it should be noted that these demonstrate correlations and not causal relationships.

The interaction effects were also shown to be significant, where the relationship for vaccine belief efficacy and social distancing increased for unvaccinated (M = 0.96; SE = 0.16) and partially vaccinated individuals (M = 0.56; SE = 0.38). However a negative association was shown between vaccine belief efficacy and social distancing unvaccinated

(M = -0.14; SE = 0.11). These results would suggest that as individuals propensity for social distancing increases, they are more likely to hold stronger vaccine beliefs if partially or unvaccinated. However, fully vaccinated individuals demonstrate little change in their vaccine belief as they vary in social distancing. These results show that the interaction is significant for Unvaccinated individuals (β = 0.96, $p < .001$); however the interaction effect was not significant for partially vaccinated (β = 0.56, p = 0.143) or fully vaccinated individuals (β = -0.14, p = 0.18).

3.6.2 Regressing vaccine status & social distancing on COVID-19 risk belief. To explore possible explanations of how COVID-19 risk beliefs influence social distancing across vaccine states, a fixed-effects linear regression was conducted, as specified below regressing vaccine status (interacted with averaged social distancing across all trials) on log-transformed COVID-19 risk beliefs, with a vector of control variables. To correct for heteroskedasticity, White's robust standard errors are computed using the vcovHC function of the *sandwich* package (Zeileis, 2006).

$$Risk_i = Control_i + Status_i * Distance_i + \epsilon_i$$
$$\epsilon_i \sim N(\mu, \sigma)$$

The fixed-effects model shows a significant effect of social distancing (β = 0.13, p = 0.022), where higher risk beliefs are associated with increased distancing. The model demonstrates an effect of vaccine status on risk beliefs, there is a significant difference between partial and fully vaccinated risk perceptions (β = 1.24, p = 0.009). However, there is no difference between fully vaccinated and unvaccinated individuals (β = -0.17, p = 0.534). Estimated marginal means shows that partially vaccinated individuals hold the highest risk perception (M = 2.77%; SE = 0.20), followed by unvaccinated individuals (M = 2.37%; SE = 0.13) and lastly fully vaccinated individuals (M = 2.25%; SE = 0.11). Interaction effects of vaccine status and averaged social distancing are not significant which would suggest there is no moderation effect for social distancing on risk perception for different vaccine statuses ($p < .05$).

3.6.3 Intention to vaccinate. Further exploratory analysis is conducted to explore subgroup analysis of unvaccinated individuals, to examine whether belief in the vaccine is motivated through other rationale (political) which may be an extraneous factor. To investigate this, exploratory analysis was conducted on whether vaccine intentions have any effect of social distancing. An additional analysis was conducted on the effect of upcoming vaccination appointments on social distancing.

To investigate, the following model was fitted to the subset of sample who self-report as unvaccinated.

$$Distance_{i,j} = Control_i + Intent_i * Belief_i + Location_{i,j} * Activity_{i,j} + (1|subjID_j) + \epsilon_i + \lambda_j$$
$$\epsilon_i \sim N(\mu_1, \sigma_1),\ \lambda_j \sim N(\mu_2, \sigma_2)$$

Where "*Intent*" refers to either intention to get vaccinated or an upcoming vaccine appointment as a boolean variable; Control denotes a vector of control variables (age, sex, hospital employment, state, ethnicity, employment).

When modelling the effects of vaccine intentions, there is a no effect of vaccine intentions ($F(1, 101) = 1.92$, $p = 0.168$). The model demonstrated an effect from vaccine belief, where individuals who hold stronger beliefs demonstrate a greater liklihood to socially distance ($F(1, 101) = 0.26$, $p = 0.61$), where for every one unit increase in belief, unvaccinated individuals are willing to stand 0.233m further.

There was a significant interaction effect between vaccine intentions and vaccine beliefs, ($F(1, 101) = 6.03$, $p = 0.016$), where individuals intending to vaccinate socially distance 0.0542m less for every one unit increase in belief ($t(102) = -0.19$, $p = 0.016$). To visualise such effects predicted distance values were plotted across activities against the raw belief scores as shown in Figure 6 below. One causal explanation may be that not intending to get vaccinated is negatively associated with the percieved effectiveness of the vaccine (i.e. individuals who do not intend to get vaccinated do not percieve the vaccine as effective), or risk of COVID-19 (individuals who do not intend to get vaccinated hold lower propensity beliefs of acquiring a COVID-19 infection than individiuals who do intend to get vaccinated) as well as the political recourse and trust.

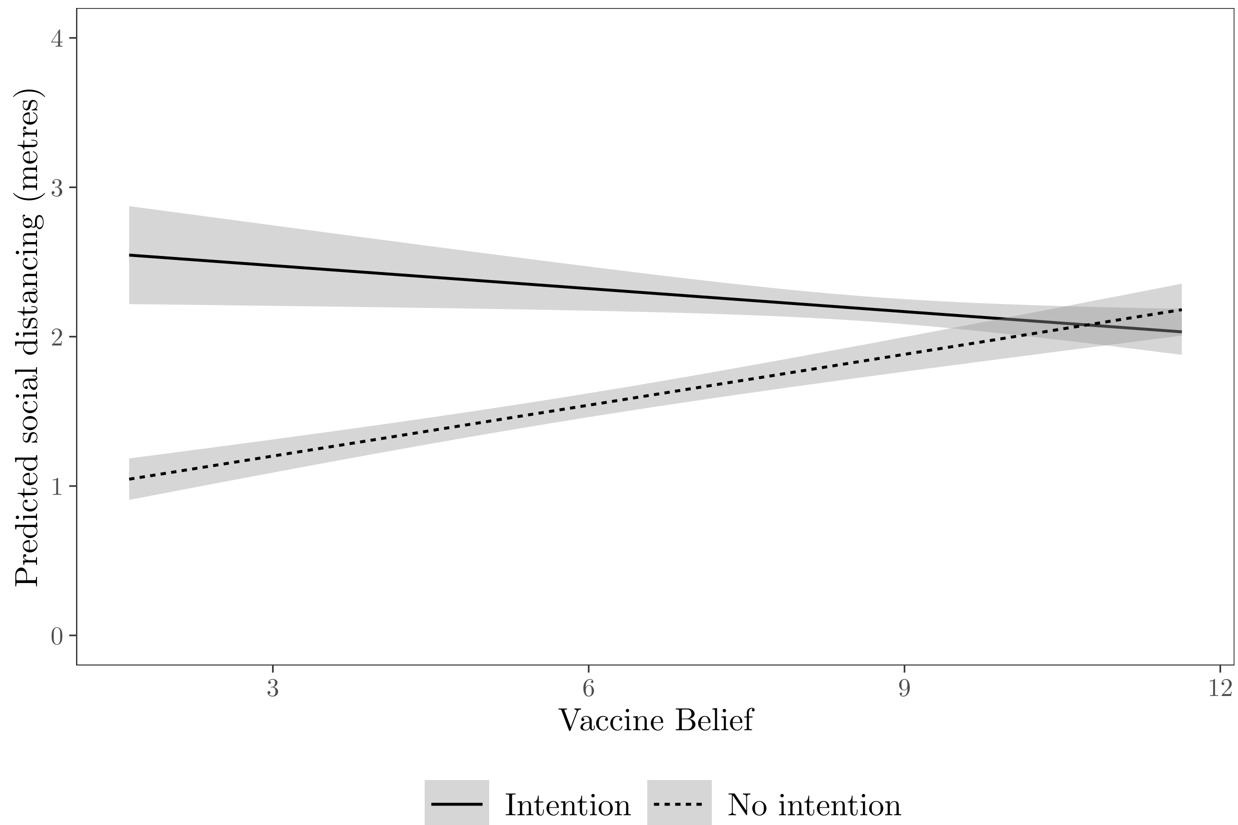

Figure 6. Line graph showing how when vaccine belief increases in unvaccinated populations, individuals with no vaccine intention socially distance further, whilst indiviuals with an intention to get vaccinated reduce social distancing as their belief grows stronger, (*note: Error bars reflect S.E.M*).

To explore this assumption further an additional fixed-effects regression was ran regressing COVID-19 risk beliefs of acquiring an infection on vaccine intention interacted with vaccine belief, including the vector of control variables with location and activity as fixed effect terms. This model reveals a significant difference between vaccine intentions (β = 4.54, $p < .001$), with individuals holding a vaccine intentions estimating their chances of acquiring COVID-19 at 21.23% (95% CI: 18.26; 24.19) whilst individuals who do not intent to get vaccinated hold their probability judgements lower at 24.26% (95% CI: 21.75; 26.77). There is only a marginal effect for the interaction of vaccine intentions and vaccine belief

(β = 0.92, p = 0.072).

3.6.4 Effect of vaccine appointment. When exploring the impact of vaccine appointment on social distancing a fixed-effects linear model was conducted given the limited sample size of unvaccinated participants and likelihood of a participant having an upcoming appointment. The model revealed a significant effect of age (β = -0.02, $p <$ .001), with older participants less likely to socially distance.

Post-hoc comparisons revealed the same pattern of ordering os observed previously. Sitting is associated with the greatest social distancing (M = 2.54m, SE = 0.259) compared to walking (M = 2.09, SE = 0.259) or standing (M = 1.91, SE = 0.259) (p < .001 respectively). With walking showing greater distancing than standing (t (835) = -9.376, $p <$ .001). There is also an effect of sex (β = -0.20, p = 0.012), with females showing they are more likely to socially distance than males. There was an effect of vaccine appointments (β = 0.47, $p <$ .001), with individuals who hold appointments estimated to position themselves at 2.39m (95% CI: 2.00m; 2.78m), whilst individuals who dont have appointments stand closer 1.79m (95% CI: 1.63m; 1.94m). These results are in direct contrast fo H_6, this may be due to an association of having booked/accepted a vaccine appointment to underlying beliefs in the the risk of COVID-19, illustrated in Figure @ref{mod6}.

3.6.5 Judgements on vaccine status distributions. Exploratory analysis examines the perceived distribution of vaccine status, i.e. the percentage of people participants believe are unvaccinated, partially or fully vaccinated. To investigate, linear fixed effect models were conducted with the following specification:

$$Outcome_i = Control_i + Status_i * Belief_i + (1|subjID_j) + \epsilon_i \ \epsilon_i \sim N(\mu, \sigma)$$

Where Outcome denotes subjective distribution of either fully vaccinated, partially vaccinated or unvaccinated, with Vaccine Status denoting whether participant is fully vaccinated, partially vaccinated or unvaccinated. To correct for heterskedasticity, White's

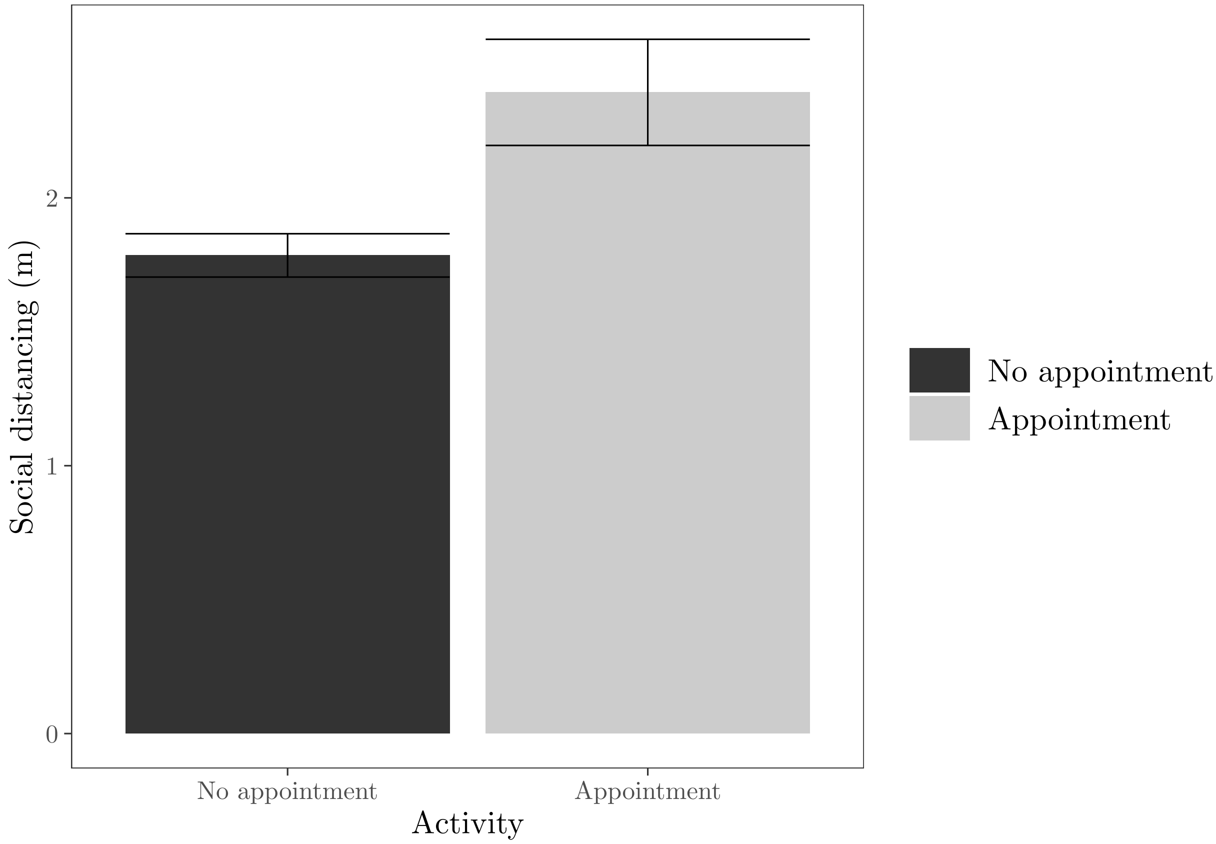

Figure 7. Bar graph demonstrating unvaccinated individuals with upcoming vaccine appointments social distancing less than individuals without an appointment (error bars reflecting SEM).

robust standard errors are computed using the vcovHC function of the sandwich package (Zeileis, 2006).

Across the three models there is a significant effect of healthcare worker status ($p <$ .001), where healthcare workers hold lower judgements for fully vaccinated (M = %; SE = 1.17) and higher judgements for partially (M = %; SE = 0.90) and unvaccinated (M = %; SE = 1.13) compared to non-healthcare workers. The model also demonstrates find a consistent effect of Asian and Black or African American ethnicities ($p <$ .001), where Asian participants hold greater estimates for fully vaccinated (M = 40.56%; SE = 0.94) and partially vaccinated (M = 25.82%; SE = 0.94), with lower judgements for unvaccinated populations (M = 40.56%; SE = 0.94)in comparison to White Americans; conversely Black and African Americans tend to underestimate fully vaccinated (M = 31.54%; SE = 1.01), but have greater estimates for partially (M = 27.88%; SE = 1.01) and unvaccinated populations (M = 40.58%; SE = 1.01) in comparison to White Americans. White Americans were shown to estimate M = 36.32% (SE = 0.73) of the population to be fully vaccinated; M = 25.18% (SE = 0.56) of the population to be partially vaccinated; and 38.50% (SE = 0.70) of the population to be unvaccinated. The model also reveals a significant effect of vaccine belief, where individuals who hold stronger beliefs estimate greater fully vaccinated populations ($\beta = 1.44$, $p = 1.437$). Yet stronger held vaccine belief negatively predicted the judgements for partially vaccinated ($\beta = -0.54$, $p < .001$) and unvaccinated ($\beta = -0.90$, $p < .001$) populations.

When evaluating the effects of vaccine status on perceived distributions of vaccinates, there is evidence in favour of egocentric mechanism influencing distribution judgements, wherein individuals hold their own vaccine status as the most probable. This is best shown in Figure 8. For estimates of fully vaccinated populations, individuals who were fully vaccinated held the highest judgements (M = 42.61%; SE = 0.92), with partially vaccinated individuals (M = 34.57%; SE = 1.33) and unvaccinated individuals (M = 33.47%; SE = 1.01) holding significantly lower estimates ($p < .001$). There are no significant differences between estimates of fully vaccinated populations for partial and unvaccinated individuals ($\beta = 1.10$, $p = 1.103$).

For estimates of partially vaccinated populations, individuals who were partially vaccinated held the highest judgements (M = 32.08%; SE = 1.02), with fully vaccinated individuals (M = 23.32%; SE = 0.71) and unvaccinated individuals (M = 23.71%; SE = 0.78) holding significantly lower estimates ($p < .001$). There are no significant differences between estimates of partially vaccinated populations for fully and unvaccinated individuals ($\beta = 9.15$, $p = 9.147$).

For estimates of unvaccinated populations, individuals who were unvaccinated held the highest judgements (M = 33.35%; SE = 1.27), with fully vaccinated individuals (M =

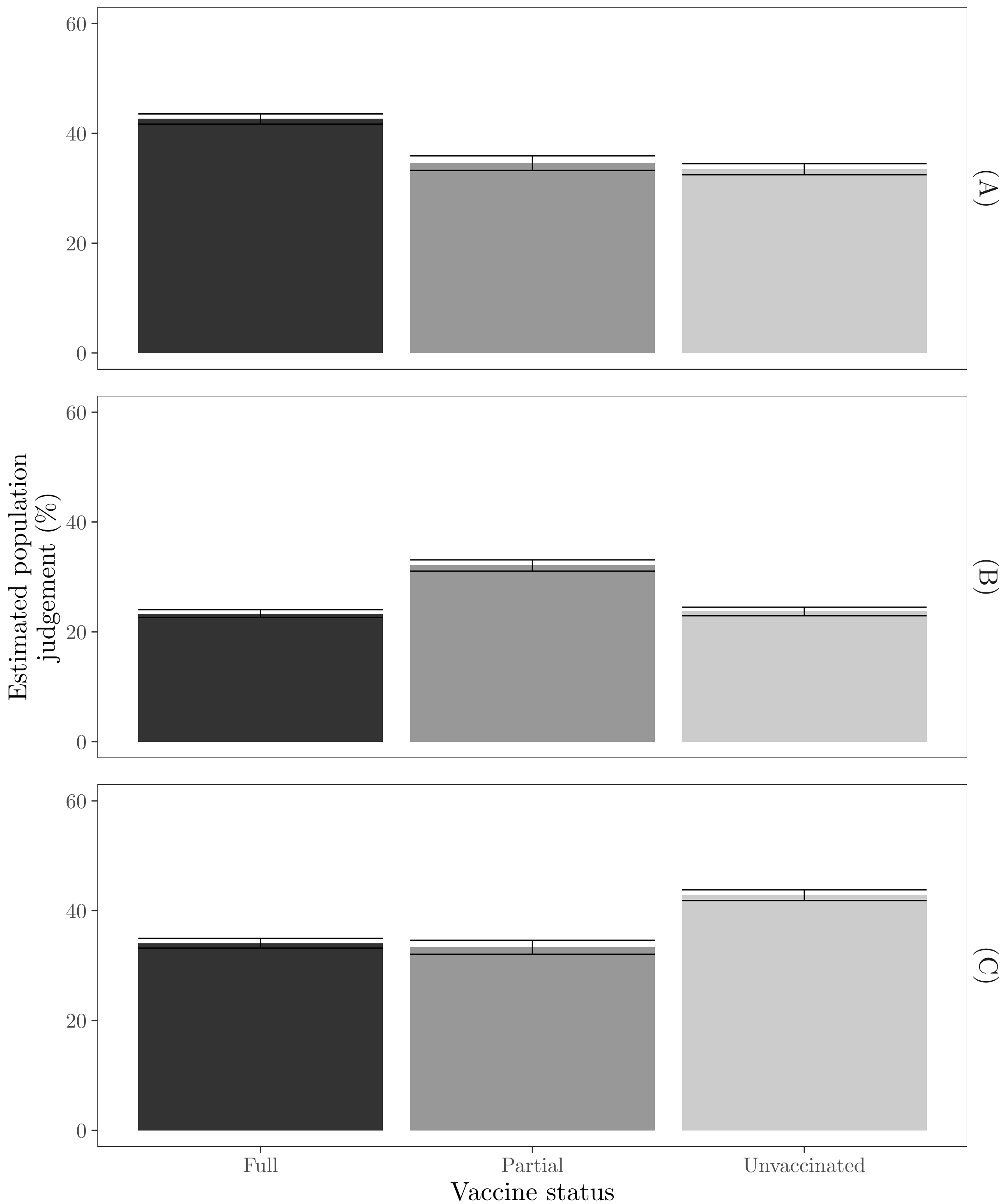

Figure 8. Bar graph of subjective percieved distribution of each vaccination status populations showing an in-group bias in judgement formations. (A) Represents the estimated marginal means *judgements of fully vaccinated populations* for each vaccine status, (B) Represents the estimated marginal means *judgements of partially vaccinated populations* for each vaccine status; (C) Represents the estimated marginal means *judgements of unvaccinated populations* for each vaccine status.

34.07%; SE = 0.89) and unvaccinated individuals (M = 42.82%; SE = 0.97) holding significantly lower estimates ($p < .001$). The estimates mean judgements of fully and partially vaccinated individuals were shown to be significant differences ($\beta = 9.15$, $p <$ .001).

3.6.6 Vaccine manufacturer and vaccine belief. Further analysis was conducted to explore differences as a direct consequence of the strain of vaccinations provided (whether from Pfizer, Moderna, AstraZeneca or Johnson & Johnson), to this aim, qualitative comparisons were conducted of stated and revealed preferences of social distancing as expressed through vaccine belief statements and social distancing judgements respectively.

To investigate the effect of vaccine manufacturer on vaccine belief, a fixed-effects linear regression was conducted, regressing vaccine belief on the different vaccine manufacturers with a vector of control variables. This model includes vaccine manufacturer and not vaccine status, as not all vaccine manufacturers provide multiple doses for full immunity, meaning comparisons cannot be held between against partially vaccinated individuals. The most common vaccine manufacturer was used as the reference group (Pfizer BioNTech) and heteroskedastic robust standard errors were estimated using the *sandwich* package (Zeileis, 2006).

These results show a siginificant effect of age ($\beta = 0.01$, $p < .001$), where for each increase in year, beliefs in the vaccine grow by 0.01. There is also find a significant effect of employment ($\beta = 0.25$, $p < .001$), suggesting that employed individuals hold a stronger belief than unemployed individuals. The model reveals a significant effect for vaccine manufacturer, as demonstrated in Figure 9. Pfizer BioNTech is associated with highest belief in vaccine efficacy (M = 7.53; SE = 0.07), compared to Johnson & Johnson which expressed the lowest held belief (M = 6.89; SE = 0.13; $\beta = -0.64$, $p < .001$); as well as Moderna (M = 7.19; SE = 0.08; $\beta = -0.34$, $p < .001$) and even Oxford/AstraZeneca (with an estimated mean of (M = 7.14; SE = 0.16; $\beta = -0.40$, $p < .001$).

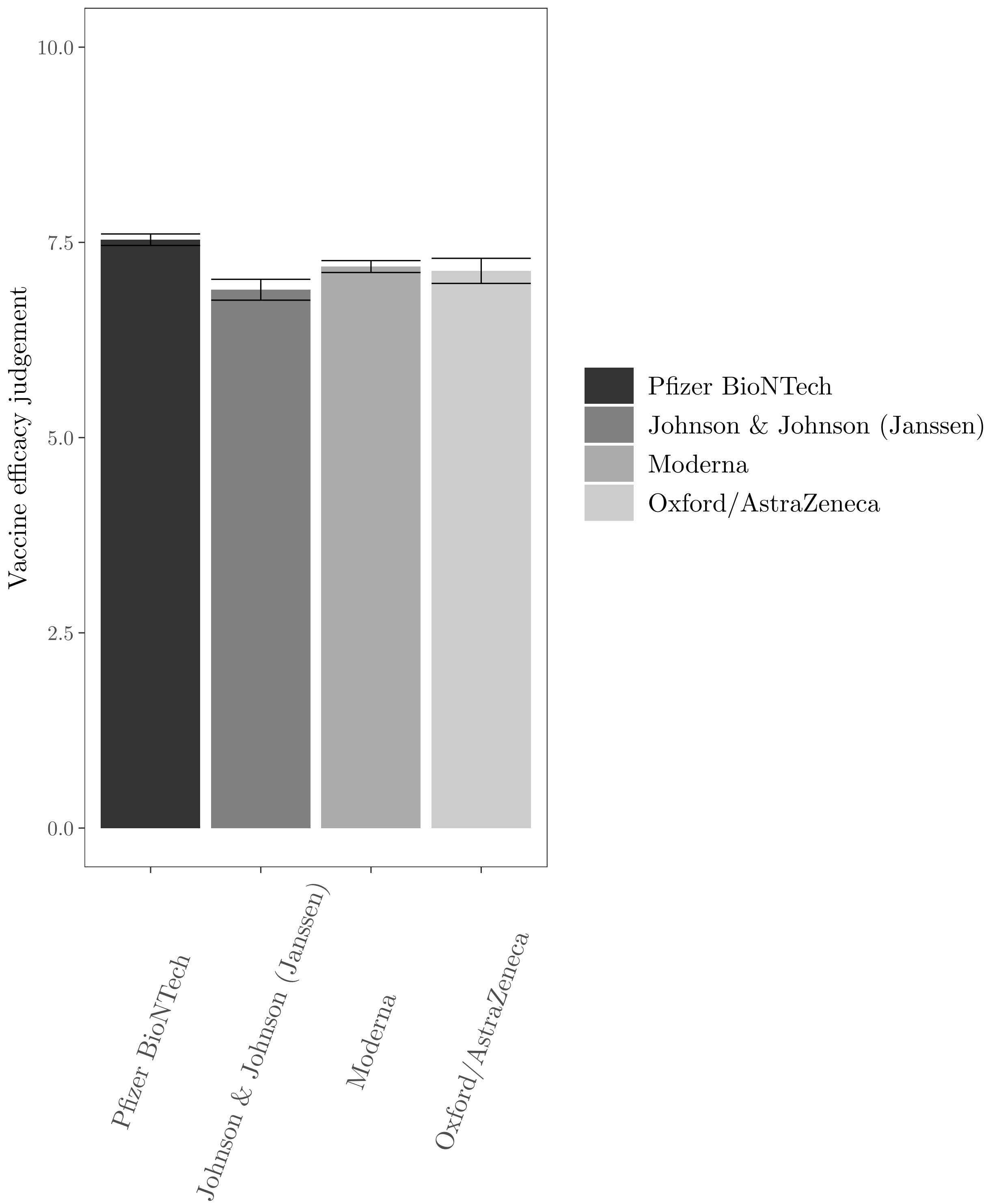

Figure 9. Bar graph showing mean vaccine belief across different vaccine manufacturers, with strongest beliefs held by Pfizer BioNTech vaccine recipients, followed by Moderna, then Oxford/AstrZeneca(*note: Error bars reflecting SEM*).

3.7 Vaccine manufacturer and social distancing

To investigate the effect of vaccine manufacturer on vaccine belief, a mixed-effects linear regression was conducted regressing vaccine belief on the different vaccine manufacturers, including the vector of control variables with a random effect for each subject. This model also includes vaccine manufacturer and not vaccine status, as not all vaccine manufacturers provide multiple doses for full immunity, meaning comparisons cannot be held between fully and vaccinated individuals. The most common vaccine manufacturer was used as the reference group (Pfizer BioNTech).

Investigating the effect of vaccine manufacturer on social distancing, as a form of revealed preferences was able to replicate the effects for location (F(1, 2360) = 46.82, $p <$ .001) and activity (F(2, 2360) = 348.01, $p < .001$). The model also demonstrates that individuals do not differ in their degree of social distancing as a function of vaccine manufacturer (F(3, 422) = 0.79, $p = 0.497$) this is exemplified on Figure 10.

4 Discussion

This study investigated the use of social distancing task in an online setting to estimate population differences between different vaccine states in social distancing across different settings. The results demonstrate greater beliefs in vaccine efficacy is met with greater social distancing. However there is a moderated effect of vaccine belief for different vaccine states on social distancing. Unvaccinated and partially vaccinated individuals socially distance further as their belief in vaccine efficacy grows. However it was observed for fully vaccinated individuals that they would socially distance less as their belief in vaccine efficacy grows.

When exploring the underlying conditions, the results showed significant population differences in average strength of beliefs, with fully vaccinated individuals holding the strongest beliefs, closely followed by partially vaccinated and then unvaccinated individuals. These population differences may represent possible underlying personality or

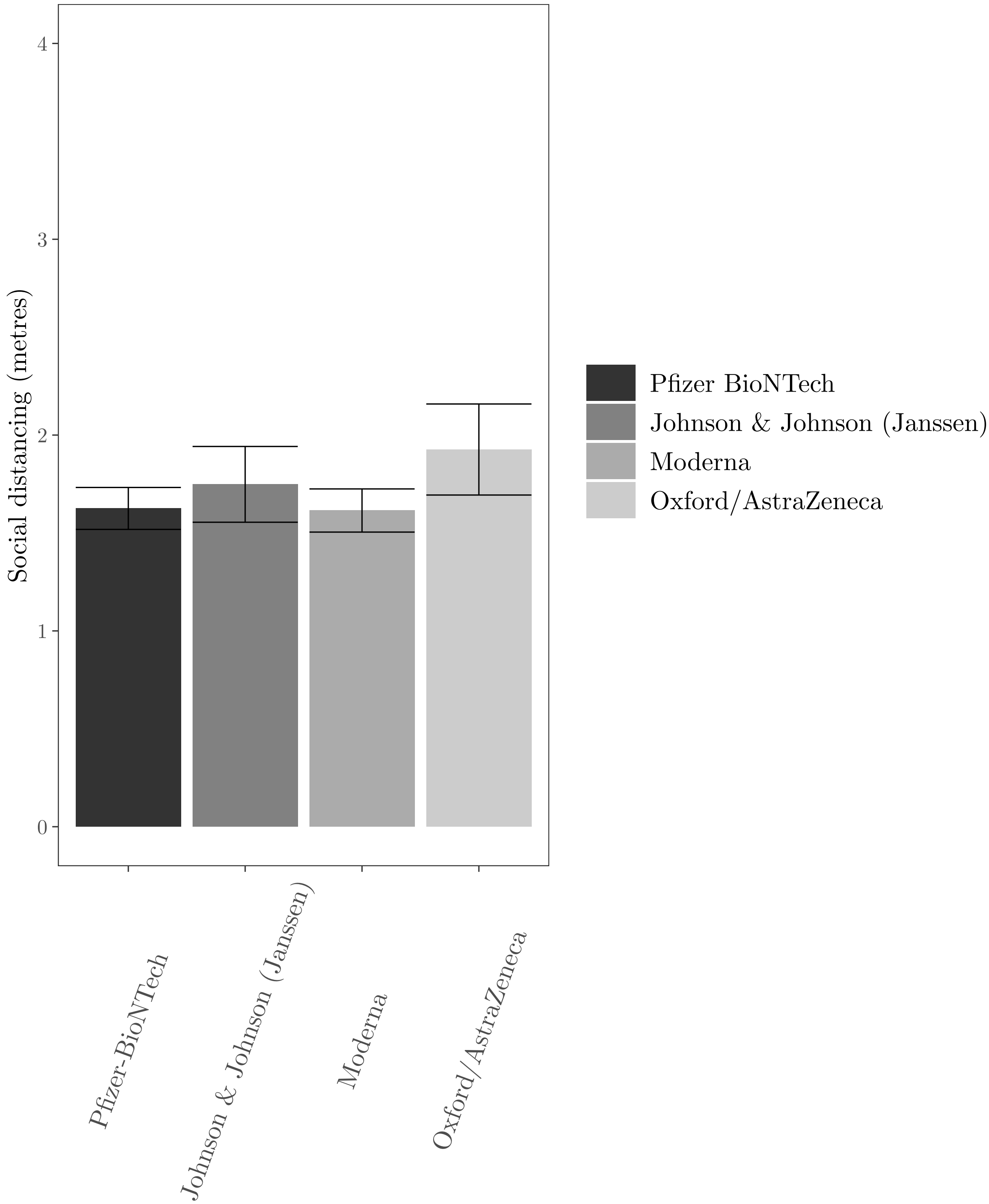

Figure 10. Bar graph showing no difference in estimated mean social distancing across vaccine manufacturers (*note: Error bars reflecting SEM*).

risk differences. For example, it may be likely that individuals who hold very high beliefs in vaccine efficacy are more likely to get vaccinated earlier and may be further along the vaccination pathway than others (partially vaccinated). Whilst, the low vaccine belief held by unvaccinated individuals may represent their underlying vaccine hesitancy. However, as these are population differences these are correlational associations and no causal inferences can be made.

These results are consistent with risk compensation demonstrating population differences in perceived risk, beliefs in vaccine efficacy and social distancing as a function of vaccine status. This finding is likely the result of competing signals of risk (risk of COVID-19, belief in vaccine efficacy and the effects of social distancing), as a consequence different populations can likely amplify different signals of risk and will adjust their behaviour accordingly to moderate the overall risk exposure. Increase in vaccine belief for those who are vaccinated is associated with reduced physical distancing, whilst partially and unvaccinated populations increase social distancing as their belief in vaccine efficacy increases. These interactions are consistent with risk compensation, as the participants who perceive the greatest reduction in risk because they believe masks provide protection also engage in the greatest extent of risk compensation behaviour (Luckman et al., 2021; Underhill, 2013).

These results do conflict with the findings of Sun et al. (2022), who found that vaccinations were not associated with risk compensation. However, an important distinction between these two studies were that the behaviour directly measured was in handwashing whilst in this study was social distancing. The link between the two measures in the present study is closer than by Sun et al. (2022). Furthermore, the context is different with US citizens in the current study compared to Chinese citizens, and the study design uses an online natural experiment, whilst Sun and colleagues employed a field experiment measuring real-world behaviour. The results are consistent Buckell et al. (2021), who demonstrated risk compensation in a field setting using survey methods.

In addition to the main finding of risk compensation, the results suggest that vaccine intentions are also linked with risk compensatory behaviours, where individuals will willingly reduce social distancing if they intend to get the vaccine. Exploratory analysis also demonstrated a motivated reasoning of perceived vaccination distributions, where individuals held significantly greater judgements for their estimates of the proportion of their own vaccine status groups over others.

The implications of these findings for governmental policy on public health measures surrounding social distancing. If the policy is for physical distancing across the board, then vaccinations may lead to reduced social distancing once the vaccine rollouts reach a critical mass. This is a crucial time in which mutated strains could post a threat to public health (Hossain, Hassanzadeganroudsari, & Apostolopoulos, 2021; Madhi et al., 2021). It is possible that policymakers are aware of the issue of risk compensation and that such policy may even have a perverse effect of increasing the absolute risk of viral transmission.

This study does demonstrate evidence of risk compensation, but more information is required to ascertain whether transmission is impacted by vaccinated individuals reducing their social distancing. Future research should replicate the findings in a field setting, using tracking data to monitor for location and distancing between strangers. Furthermore, further research may be warranted to identify the construct validity of using avatar-based online research as preferences of scaled distancing.

In future pandemic situations, where the goal of public health policy is to reduce transmission rates, then people's willingness to compensate vaccination efficacy for social distancing may be problematic if mutated strains emerge that the vaccine do not permit significant protection against. In this situation, this study's results would suggest that transmission rates would increase as a result of vaccination. It would therefore be of value for policy makers to produce guidelines of vaccination provide sufficient clarity regarding their value and efficacy in the specific contexts they apply. For instance, by placing importance on vaccination compliments social distancing as opposed to being an alternative interventional means, may improve public health compliance. Future research should test such behavioural interventions (Bavel et al., 2020; West, Michie, Rubin, & Amlôt, 2020).

It should be noted that the experiment focused on a US sample, but that similar results would likely be observed if using similar sample populations with similar public health policies. These results could be particularly relevant especially given the delta and omicron variants which were found to be 50-70% more transmissible (Hossain et al., 2021). In the context of a mutation, countries would need to enforce greater social distancing to allow for risk compensation and act as a potential anchor of physical distancing.

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