

Behavioral effects of anti-pandemic preventive measures: a VR study

Abstract

Objective: The behavioral consequences of COVID-19 preventive measures on human navigation in shared public spaces remain largely unexplored. We investigated how mask-wearing and perceived environmental safety influenced social wayfinding and proxemic behavior during the pandemic. **Methods and Measures:** Using immersive virtual reality, 29 participants navigated rooms containing virtual human agents. We systematically manipulated three factors: participants' mask status, agents' mask status, and perceived environmental safety (high versus low community vaccination rates). We measured initial path selection decisions and subsequent interpersonal distance maintenance. **Results:** Initial path selection was primarily determined by agent mask-wearing, with participants preferring to pass in front of masked versus unmasked agents. Perceived environmental safety predominantly governed interpersonal distance, with closer proximity maintained in high-vaccination contexts. Participants' own mask status had minimal influence, suggesting navigational choices were driven by external risk assessment rather than personal protection. Clear risk compensation emerged: participants reduced interpersonal distance in safer conditions (whether environmental, agent masking, or personal masking). Bayesian model comparisons favored a three-factor additive model, indicating independent rather than interactive behavioral influences. **Conclusion:** These findings reveal the complex decision-making underlying pandemic-era social navigation and highlight the critical importance of accounting for risk compensation behaviors when designing effective public health interventions.

1 Introduction

1.1 Background

The COVID-19 pandemic has profoundly altered social interactions and the way people navigate public spaces, presenting unprecedented challenges to social norms (1; 2). Although the acute phase of the crisis has subsided, COVID remains a potential threat, as do a variety of other viruses such as seasonal and zoonotic influenzas (3) and even measles (4; 5). As we consider this post-pandemic landscape, it is crucial to understand the efficacy of various preventive measures and their impact on how humans navigate shared spaces.

While lockdowns were widely implemented to mitigate viral transmission (6), their efficacy and socioeconomic consequences have been intensely debated (7; 8). In future health crises, less disruptive non-pharmaceutical interventions (NPIs) such as social distancing and mask wearing are likely to be prioritized (9; 10). However, the actual effects these measures have on navigational behaviors remains poorly understood (11; 12), particularly their potential interactions (13; 14; 15). Since multiple preventive measures are often implemented simultaneously, examining their combined effects on social locomotion patterns can reveal whether they reinforce or potentially undermine each other's intended behavioral outcomes.

This paper investigates the behavioral consequences of pandemic-era policies using virtual reality (VR) to test human subjects navigating simulated public spaces. We examined how participants' chosen paths varied as a function of mask-wearing (by themselves and virtual agents) and perceived environmental safety (high versus low vaccination rates). To our knowledge, this represents one of the first experiments combining mask-wearing and perceived environmental safety in predicting social navigation through avoidance behavior and social distancing.

1.2 Mask wearing

During the COVID pandemic, mask use and social distancing emerged as the most prevalent and crucial NPIs. Since the virus was transmitted through respiratory droplets (16), masks reduced the probability of transmission during interactions, while social distancing reduced the frequency of such interactions occurring (17).

Studies have shown that wearing face masks and maintaining physical distance can significantly decrease the risk of COVID-19 infection (18; 19). Higher rates of mask usage are correlated with lower transmission rates and reduced COVID-19 cases (20; 19; 21). Masks are particularly effective in settings where social distancing can be difficult to maintain, such as indoor environments (22).

Despite their importance in infection prevention, mask adoption was initially controversial, particularly in the United States, where early shortages led to recommendations against mask use for healthy individuals, complicating later mask mandate enforcement (23).

Furthermore, our understanding of mask efficacy has evolved over time. The initial consensus focused on masks protecting individual wearers, but later evidence indicated that their primary function is "source control" - that is, limiting droplet dissemination from potentially infected and asymptomatic individuals (22). Although masks provide moderate protection for users from inhaling small viral particles, they are significantly more effective in preventing infected individuals from spreading larger respiratory droplets to others (24). This asymmetry in mask efficacy raises an important question that we will tackle in this study, regarding risk perception: whether individuals weight their own mask-wearing more or less heavily than that of others when assessing potential infection risk and making navigational decisions.

1.3 Social distancing

Social distancing measures, while less contentious than mask mandates, significantly impacted various sectors, particularly the food service industry and public-facing services, leading to widespread adjustments to accommodate spatial requirements (25; 26; 27). Public health authorities recommended maintaining a physical distance of at least 1.5-2 meters (approximately 5-6 feet) between individuals to reduce viral transmission (25). This guideline significantly altered social navigation in public spaces, as it was in conflict with typical proxemic behavior in which people maintain smaller interpersonal distances of approximately 1 meter when interacting with unfamiliar individuals (28; 29). The implementation of social distancing, coupled with occupancy restrictions, fundamentally changed how people moved through and interacted in shared environments, presenting novel challenges for urban planning, crowd management, and the design of public spaces (9).

These changes in social norms required rapid adaptation of individual behaviors and spatial cognition. Studies revealed significant alterations in personal space preferences and interpersonal behaviors during the pandemic (30; 31). Changes in spatial behavior varied between populations and contexts, influenced by cultural norms, individual risk perception, and local infection rates (32; 33).

1.4 Risk compensation

Recent research has examined the interplay between mask use and social distancing in reducing virus transmission (14; 15). Mathematical modeling has illustrated how the combination of mask-wearing and social distancing can effectively reduce virus spread, particularly in populations with a high percentage of asymptomatic carriers (14). Thus, mask-wearing is a crucial complementary measure to social distancing in mitigating pandemic spread (15).

However, the relationship between these preventive measures is complex (34). Wearing masks can alter social interactions, potentially reducing interpersonal distance and affecting emotional responses during social encounters (31). This suggests that masks not only serve as a physical barrier, but also modify social interactions and perceptions of safety in public spaces (35).

Reducing interpersonal distances from masked people may be expression of risk compensation, where adopting one preventive measure may lead to reduced caution in other areas (36). The concept of risk compensation, which is rooted in behavioral economics (37; 38), suggests that people adjust their behavior in response to perceived changes in risk (39). In the context of COVID-19, protective measures like mask-wearing could lead people to relax their adherence to other preventive behaviors, such as maintaining physical distance or hand hygiene (40), under the assumption that the adopted measure provides sufficient protection, which could lead to an overall increase in risk-taking behavior (41). The extent and impact of risk compensation in pandemic scenarios remain subjects of ongoing debate and research (42).

At the beginning of the pandemic, some data suggested minimal risk compensation (43), but subsequent studies have provided some evidence of risk compensation behaviors (44; 41). In a virtual reality experiment, Krocze et al.(12) found that wearing face masks reduced the minimal interpersonal distance participants maintained with virtual agents in a simulated supermarket environment. This effect was observed both when participants wore masks and when virtual agents wore masks. Importantly, the study revealed that this risk compensation behavior was most pronounced when maintaining the recommended distance of 1.5 meters required additional effort, and participants had to actively circumvent the virtual obstacle. This finding suggests that situational constraints play a crucial role in how protective measures influence social distancing behaviors. In addition to supporting the presence of risk compensation behaviors, Xiong et al. (45) used virtual reality to examine how face masks influence interpersonal distance during the COVID-19 pandemic. They found that participants maintained smaller distances when interacting with virtual confederates wearing masks compared to those without masks.

1.5 Environmental context

Beyond NPIs, social behavior and navigation are potentially influenced by the general perception of safety from contagion, including such factors as adherence to protocols, restrictions, and vaccination uptake (46). Collective acceptance or rejection of these measures shapes the overall perceived risk of infection and therefore individual choices (47). Individuals in areas with widespread non-compliance perceive a higher risk of COVID-19 infection (48). On the other hand, knowledge of high local vaccination rates increases vaccine uptake (49), a phenomenon attributed to herd behavior (50). Paradoxically, this can then reduce NPI compliance (46; 51), potentially fueling viral resurgence during ongoing vaccination efforts.

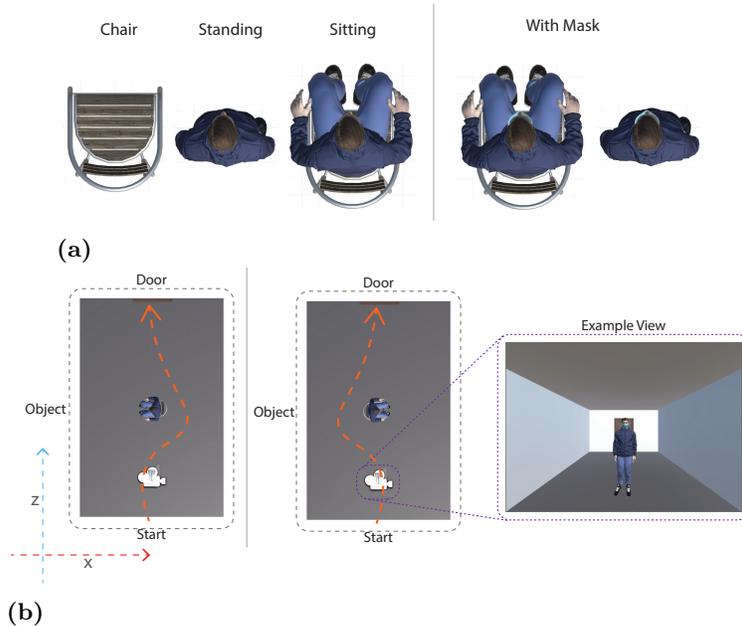


Fig 1. (a) The obstacles used for the virtual rooms. Each obstacle is rotated in all 4 cardinal directions. (b) Illustration of possible pathways around obstacles. To the right, an example of the participants view of the obstacle at the start of the study.

2 Experiment

2.1 Overview

VR offers key advantages for studying pandemic behavior: it provides consistent, repeatable experimental conditions that would be difficult or unethical to replicate during an active pandemic (52; 53), and it enables precise measurement of navigation behavior (54; 55) rather than hypothetical characterization as in online studies (41). We conducted our study in spring 2022, when the pandemic was evolving rapidly. Community mask mandates remained in place following the Omicron variant surge, yet a period of moderate normalization was underway, with growing recognition of the need for new habits and procedures—including everyday navigation patterns—as part of the “new normal.” Our study aimed to quantify the pandemic’s disruptive effect on social wayfinding.

3 METHODS

3.1 Experimental Design

Data were collected from 33 participants (17 women, 16 men; mean age 19.5 years, SD 1.28). We excluded 3 participants because they did not follow instructions and 1 participant because of incomplete data. All participants gave informed written consent; the protocol was approved by the institutional review board of XXX University (Protocol E17-556; approval date: May 4th, 2017). Participants were recruited over two months, from February 15th, 2022 to April 15th, 2022, through flyers posted in the XXX community. Participants received monetary compensation for their participation. All participants were vaccinated against COVID-19.

Wearing an Oculus Quest 2 headset, participants physically walked back and forth

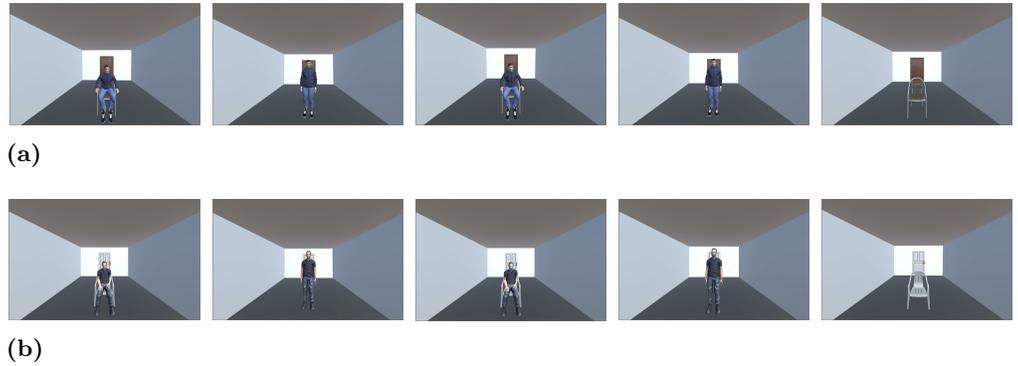


Fig 2. *Obstacle types in Exp. 3 (forward-facing condition only): (a) Scene 1: sitting agent without mask, standing agent without mask, sitting agent with mask, standing agent with mask, empty chair; (b) Scene 2: same sequence of obstacles in an alternative setting.*

inside an empty room, navigating a sequence of virtual rooms. In each room, they traversed from one end to the other while avoiding a centrally placed obstacle, then waited in an area with a fixation cross before the next trial. Over 80 trials (4 blocks of 20 rooms), the obstacle varied: a standing virtual agent, a sitting virtual agent, or an empty chair, each facing one of four cardinal directions (toward the participant, away, left, or right). Virtual agents could be masked or unmasked, yielding 20 different room types (Fig. 1a). Participants could also be masked or unmasked.

Beyond masking, we manipulated perceived environmental safety. Participants were presented with two pandemic scenarios: a “safe town” with high vaccination rates and protocol adherence, and an “unsafe town” with low vaccination rates and poor compliance. These were represented by two Unity scenes differing only in minor cosmetic details, with presentation order randomized between participants. Following a brief tutorial, each participant completed four blocks of 20 rooms. The blocks corresponded to a 2×2 design crossing participant mask status (masked/unmasked) with environmental context (safe/unsafe). Both block order and room order within blocks were randomized.

3.2 Data Analysis

In this study, we examined (1) participants’ discrete steering choices, in terms of their approach to virtual agents (walking in front or behind them), and (2) participants’ continuous modulation of their distance from such obstacles (termed clearance). To this end, in the analysis we only considered the cases in which the obstacle was a virtual agent facing either side. We ignored the cases in which the obstacle was either a virtual agent facing the front or the back or a chair. The presence of these conditions added variety to the setup but was not informative to our analysis goals. We also collated the cases in which the agent was sitting or standing and the cases in which they were facing the right or left, respectively.

To understand which preventive factor was the most influential, we conducted a series of mixed-effects regression models using STAN (via the brms R package). The models included the participant as a random effect and the NPIs or environmental context as predictors. For each model, we report the posterior estimate, the credible interval, and the *probability of direction* expressed as a p-value (56). Posterior estimates give the likely values of parameters conditioned on the data, and credible intervals give the region (comparable to a frequentist confidence interval) containing most (e.g. 95%)

of the probability density for the parameter. The probability of direction is the probability that an estimate has either a positive or negative sign, and therefore is away from zero; it can be seen as a Bayesian equivalent to the p-value.

4 RESULTS

4.1 Discrete choices: going to the front or behind the main agent

We examined whether the participants expressed a preference for going in front or behind the obstacle, when the obstacle was facing the side. For this analysis, the three independent variables were whether the situation was safe or not, whether the agent was wearing a mask or not, and whether the participant was wearing a mask or not.

The intercept term in the model, which expresses the logarithmic odds of passing behind the obstacle in the baseline condition (when the obstacle is an agent without mask, the participant has no mask, and the situation is unsafe), was statistically significant, $b = 3.26$, $SD = 0.48$, 95% CI [2.37, 4.24], $p \ll 0.001$ (see Figure 3a), indicating that the participants preferred to go behind the obstacle.

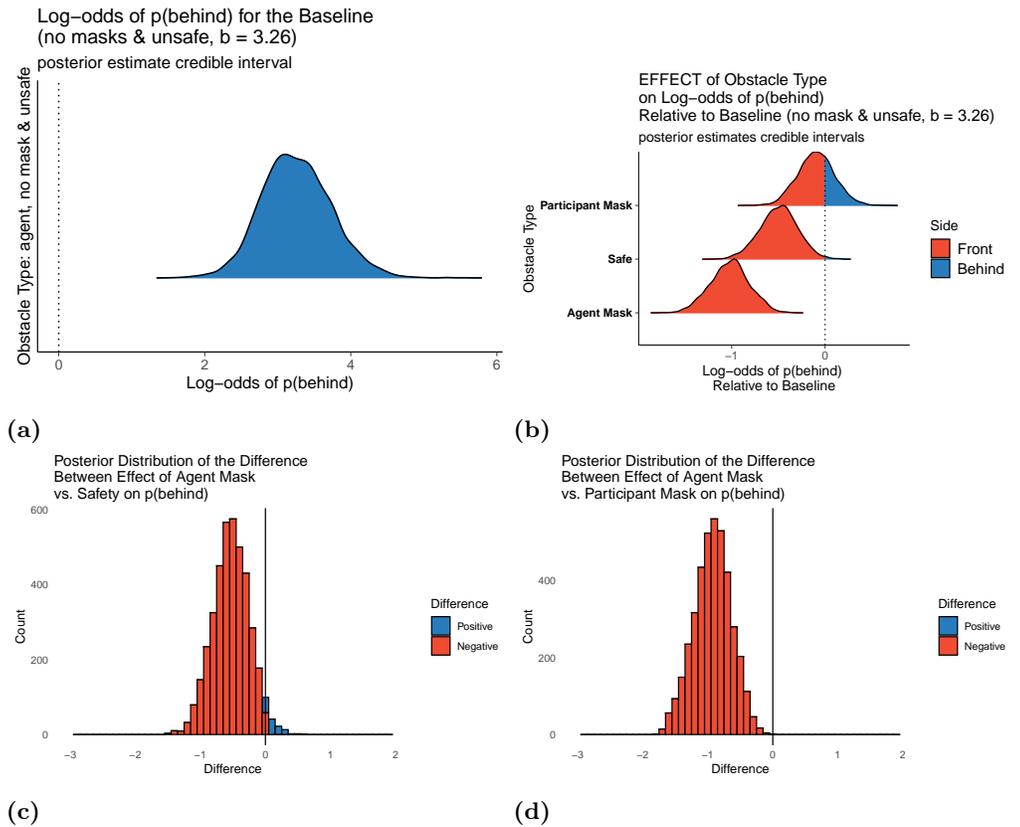


Fig 3. Posterior estimates for the log-odds of participants passing behind the obstacle: Panel (a) shows the mean point estimate and its credible interval CI for the baseline case (no masks and unsafe, $b = 3.26$); Panel (b) shows the mean point estimates and CIs for the effect attributed to each level of the IV when the other parameters are at zero; Panels (c)-(d) show the posterior distributions of the differences between the effects.

Figure 3b shows the effects for each factor. The coefficient for town safety was

statistically significant ($b = -0.50$, $SD = 0.20$, 95% CI [-0.90, -0.11], $p = 0.014$), showing a decrease of the log odds of going behind the obstacle, meaning that when the situation was considered safe, the participant was more likely to walk in front of the agent. A very strong decrease of the log odds of walking behind the obstacle was also found in the “agent mask-wearing“ condition ($b = -1.02$, $SD = 0.21$, 95% CI [-1.43, -0.62], $p \ll 0.001$), which implies that this was the most important factor when choosing whether to go behind the agent or in front of the agent. Instead, the coefficient corresponding to the participant wearing a mask was not statistically significant, with $b = -0.10$, $SD = 0.20$, 95% CI [-0.47, 0.29], $p = 0.625$, showing that whether the participant themselves was wearing a mask or not was not a big factor in determining whether the participant would go behind the agent or in front of it. In addition, there were no significant interactions between conditions.

There was a difference between the effects of agent mask-wearing and town safety, as seen by analyzing the posterior distribution of the difference between the two effects (see figure 3c), meaning that when the agent was wearing a mask, the participant was less likely to go behind the obstacle than when the situation was safe ($b = -0.53$, $SD = 0.28$, 95% CI [-1.08, 0.03], $p = 0.031$). Similarly, the participant was much less likely to walk behind the agent when the agent was wearing a mask than when the participant themselves was wearing a mask ($b = -0.93$, $SD = 0.29$, 95% CI [-1.52, -0.39], $p \ll 0.001$) as seen in figure 3d.

4.2 Clearance

We defined clearance as the lateral distance between the participant and the virtual agent at the moment of crossing the agent’s transverse plane (i.e., the imaginary line running perpendicular to the participant’s path at the agent’s location). The influence of the three primary variables on clearance is shown in Figure 4. Clearance decreased from “Unsafe“ to “Safe“ environments, a pattern also evident when agents or participants were masked versus unmasked. To identify the most influential variable, we ran a Bayesian hierarchical multivariate regression with a Gaussian prior and participants as a random variable. As before, the baseline is the case in which the situation is unsafe, and both the agent and the participants do not wear a mask.

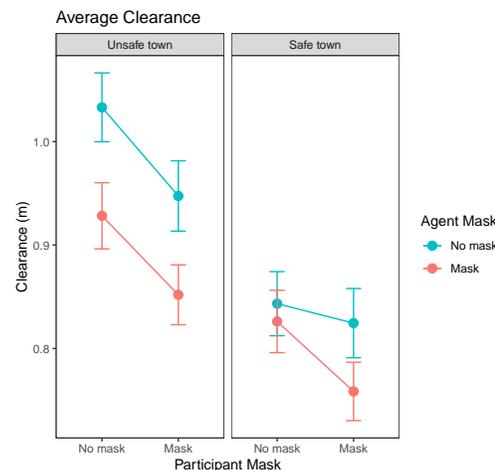


Fig 4. Average clearance as a function of the three main IVs: Average clearance as a function of participant mask status, agent mask status, and environment safety, showing approximately additive effects of all three manipulations and 95% confidence intervals

Results show that the average posterior estimate for the clearance in the baseline condition (when the obstacle is an agent without a mask, the participant is also without a mask, and the situation is unsafe), was $b = 0.99$ m, $SD = 0.05$, 95% CI [0.90, 1.08], $p \ll 0.001$ (see figure 5a). This is a fairly large clearance, although not as large as the recommended distance of 6 feet. When the situation was considered safe, there was a significant effect on clearance, which decreased $b = -0.13$ m, $SD = 0.02$, 95% CI [-0.16, -0.10], $p \ll 0.001$, indicating that in a safe situation, participants tend to get closer to the agent.

The presence of an agent mask also demonstrated a significant effect, $b = -0.09$ m, $SD = 0.02$, 95% CI [-0.12, -0.05], $p \ll 0.001$, indicating that when the agent was wearing a mask, participants walked closer to the agent. Lastly, the condition in which the participant was wearing a mask also significantly decreased the clearance, with $b = -0.06$ m, $SD = 0.02$, 95% CI [-0.09, -0.02], $p \ll 0.001$ (see Figure 5b). Overall, the safety of the situation was the most influential factor in decreasing the clearance.

There was a difference between the effects of safety and the “agent wearing a mask” condition, as seen by analyzing the posterior distribution of the difference between the two effects (5c), meaning that when the situation was safe, the participant decreased the distance from the obstacle ($b = -0.05$ m, $SD = 0.02$, 95% CI [-0.09, -0.01], $p = 0.978$) to a larger degree than when the agent was wearing a mask. Similarly, there was a difference between the effect of safety and that of the participant wearing a mask ($b = -0.08$ m, $SD = 0.02$, 95% CI [-0.12, -0.03], $p = 1.000$) showing that again the decrease in clearance was more pronounced in the safety condition than in the “participant wearing a mask” condition (5d). Finally, there was a difference between the effect of an agent wearing a mask and a participant wearing a mask ($b = -0.03$ m, $SD = 0.02$, 95% CI [-0.07, 0.02], $p = 0.899$) showing that the first condition was more influential in decreasing the clearance than the second one (5e).

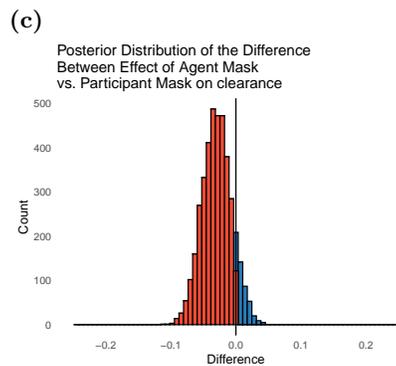
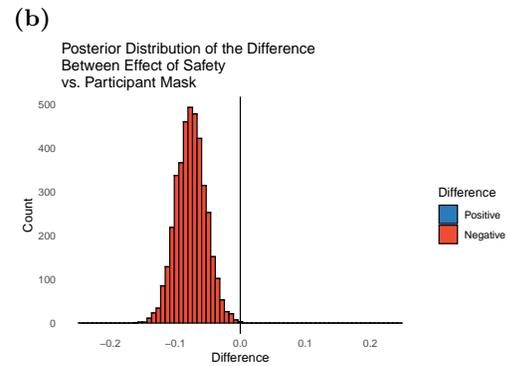
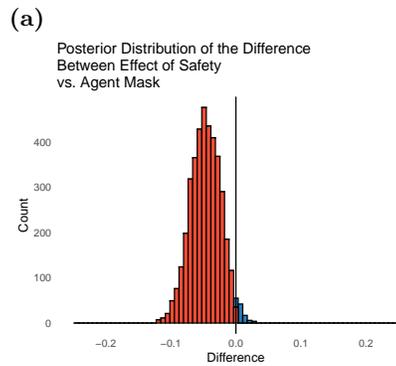
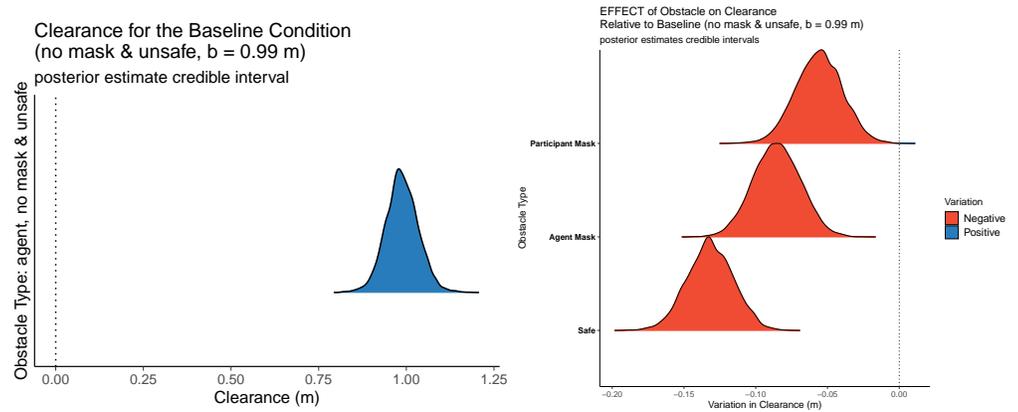
The magnitude of clearance data was also analyzed using a 2 (+/- safe environment) x 2 (+/- masked participant) x 2 (+/- masked agent) Bayesian ANOVA with participant as a random variable. The Bayesian ANOVA confirms the strength of the three factor independent model in predicting clearance. The Bayes factors for including each single factor across all models are $BF_{incl} = 2.026e+10$ for “safety”, $BF_{incl} = 226.407$ for “agent wearing a mask” and $BF_{incl} = 25.798$ for “participant wearing a mask” (see 1). This result shows that the “safety” factor is the most important one in determining clearance.

Regarding interactions, the Bayes factors for including them are very small, showing that an interaction is not needed (for example, $BF_{incl} = 0.910$ for the interaction between “safety” and “participant wearing a mask”).

Table 1. Analysis of Effects - clearance

Effects	BF_{incl}
safe	$2.026e + 10$
participant_mask	25.798
safe * participant_mask	0.427
agent_mask	226.407
safe * agent_mask	0.910
participant_mask * agent_mask	0.264
safe * participant_mask * agent_mask	0.018

A model comparison confirms this result. (see 2). The table gives two different values of Bayes factors: BF_M and BF_{10} . BF_M refers to the Bayes factor in favor of the model M. It is calculated as the ratio of the posterior odds to the prior odds for the model M. BF_{10} refers to the Bayes factor comparing the model of interest with a null



(e) **Fig 5.** *Posterior estimates for the absolute magnitude of clearance:* Panel (a) shows the mean point estimate and its credible interval CI for the baseline case (no masks and unsafe, $b = 0.99$ m); Panel (b) shows the mean point estimates and CIs for the effect attributed to each level of the IV when the other parameters are at zero; Panels (c)-(e) show the posterior distributions of the differences between the effects.

Table 2. Model Comparison

Models	BF _M	BF ₁₀	error %
safe + participant_mask + agent_mask	19.029	1.000	
safe + participant_mask + agent_mask + safe * agent_mask	4.920	0.418	5.021
safe + participant_mask + agent_mask + safe * participant_mask	2.201	0.212	12.788
safe + participant_mask + agent_mask + participant_mask * agent_mask	1.131	0.115	5.366
safe + participant_mask + agent_mask + safe * participant_mask + safe * agent_mask	0.725	0.075	4.719
safe + participant_mask + agent_mask + safe * agent_mask + participant_mask * agent_mask	0.610	0.064	15.710
safe + participant_mask + agent_mask + safe * participant_mask + participant_mask * agent_mask	0.200	0.021	7.613
safe + agent_mask	0.174	0.019	4.188
safe + participant_mask + agent_mask + safe * participant_mask + safe * agent_mask + participant_mask * agent_mask	0.084	0.009	5.697
* agent_mask			
safe + agent_mask + safe * agent_mask	0.073	0.008	4.367
safe + participant_mask	0.023	0.003	4.141
safe + participant_mask + agent_mask + safe * participant_mask + safe * agent_mask + participant_mask * agent_mask	0.018	0.002	9.523
* agent_mask + safe * participant_mask * agent_mask			
safe + participant_mask + safe * participant_mask			
safe	0.004	4.727e - 4	4.445
participant_mask + agent_mask	5.463e - 4	5.905e - 5	4.534
participant_mask + agent_mask + participant_mask * agent_mask	2.781e - 10	3.007e - 11	9.489
participant_mask + agent_mask + participant_mask * agent_mask	3.108e - 11	3.360e - 12	5.998
agent_mask	6.875e - 12	7.433e - 13	4.468
participant_mask	1.105e - 12	1.195e - 13	4.761
Null model (incl. participant)	3.454e - 14	3.734e - 15	3.830

model or baseline model. From the table, the model with three independent factors is clearly the favored one ($BF_M = 19.029$), followed by the model adding an interaction between safety and agent wearing a mask ($BF_M = 4.920$). The three factor model is used as baseline to which one can compare the other models. One can see that the value of $BF_{10} = 0.418$ for the second model would suggest that the data is 0.418 times as likely under the second model as it is under the first model.

These results confirm that multiple factors need to be taken into account when analyzing social wayfinding during a pandemic: considering factors in isolation does not explain people’s behavior.

5 DISCUSSION

5.1 Overview

To develop efficient and effective crowd management protocols during pandemics, it is important to understand how behavior is actually influenced by relevant environmental cues (33). In this study, we used a virtual reality paradigm to investigate how pandemic-related factors, specifically mask usage and perception of environmental safety, influence social navigation. We found that these factors differentially impact sequential navigation decisions: agent mask-wearing most strongly affected initial path selection (front/back choices), while the perception of environmental safety mostly influenced subsequent distance calibration. We also found that participants engaged in a form of risk compensation (36), maintaining smaller distances from the virtual agent under conditions perceived as safer. These findings extend our understanding of how preventive measures shape spatial navigation during a pandemic and highlight the complex nature of social wayfinding decisions.

5.2 Discrete steering choices

Most research on navigational decisions has focused on continuous metrics such as minimum distance, trajectory curvature, and path length (57; 58; 31). Discrete steering events are often extracted post-hoc (59) or involve symmetrical options (e.g., right/left) that are combined in analysis (60). With few exceptions (61), asymmetrical choices—such as passing in front of or behind a social agent—remain understudied, despite carrying significant social consequences including etiquette and contagion risk. Consistent with previous proxemic research (28; 62; 63; 64), we found a marked preference to pass behind agents, though this has not previously been examined in the context of pandemic-era policies. This preference was tempered by several factors. Agent mask status was the strongest predictor, with participants substantially more likely to pass in front of masked than unmasked agents. Environmental safety also mattered: participants more readily passed in front of agents in high-vaccination contexts. Notably, participants’ own mask status had negligible impact, suggesting decisions were guided by assessment of the other agent’s risk rather than one’s own protection. This may reflect awareness that masks protect others more effectively than the wearer (41; 65; 66).

These findings both complement and contrast with previous research on navigation decisions. While our work examines categorical choices with asymmetrical social valence (front versus back), Bühler et al. (60) examined symmetrical options: participants could pass to the left or right of a virtual agent oriented toward them, making both choices equivalent.

They found earlier trajectory deviations when approaching masked agents, indicating increased avoidance. Our categorical data reveal an opposite pattern: greater

willingness to pass in front of masked agents, indicating decreased avoidance. This contrast may reflect temporal differences—Bühler’s study was conducted earlier (July–November 2020)—suggesting that masks evolved from warning signals to markers of safety. Together, these findings indicate that pandemic factors shape both the timing and categorical outcomes of navigation decisions, with effects that evolve across changing public health contexts.

5.3 Clearance

Following their initial directional decision, participants calibrated the distance they maintained while passing the agent. Analysis of clearance data revealed that the most influential factors differed from those governing initial route choice. Environmental safety emerged as the primary factor, with participants maintaining significantly smaller clearances in high-vaccination versus low-vaccination settings. Agent mask status was second most influential, with participants passing closer to masked than unmasked agents. Participant mask status had the smallest, though still significant, effect. Importantly, these factors operated additively with minimal interaction effects, suggesting that participants processed each risk factor independently, with environmental context weighing most heavily. This finding partially aligns with Yu et al. (58), who observed reduced distances with masked confederates in safer conditions, and Park et al. (67), who found that environmental factors significantly modulated distancing beyond mask-wearing effects alone. However, our results diverge from Kroczeck et al. (12), who found participant mask-wearing to be the dominant factor. This discrepancy may stem from methodological differences: their participants always passed in front of the avatar without making an initial directional choice, potentially reducing the salience of the agent’s mask status. Our findings also contrast with Biggio et al. (57), who reported similar distances for masked avatars as in prepandemic unmasked scenarios, suggesting mask-wearing had become normalized. This is consistent with our finding that environmental context exerted greater influence than mask status. Collectively, these comparisons suggest that distance calibration became increasingly sensitive to contextual factors as the pandemic progressed. Bayesian ANOVA (68) provided robust confirmation: overwhelming evidence for environmental safety, strong evidence for agent mask status, and moderate evidence for participant mask status. Model comparison strongly favored an additive model without interactions, suggesting participants applied a straightforward summation of risk factors rather than complex interactive assessments. This aligns with Xiong et al. (45), who found independent effects of mask-wearing and approach patterns. Such computational efficiency may serve an adaptive function, allowing rapid distance calibration without the cognitive load of processing complex factor interactions.

5.4 Risk compensation

While the relative influence of environmental safety and masking provides important insights, we also need to take into account the consistent direction of their effects: across all three factors, safer conditions systematically led to reduced clearance distances. These findings align with Kroczeck et al.’s (12) observations of reduced interpersonal distance with mask-wearing by both participants and virtual agents. Our results are also consistent with Biggio et al.’s observation (57) of greater interpersonal space between unmasked avatars. These results demonstrated clear evidence of risk compensation (69; 37), with participants moving closer to the agent whenever protective factors were present, whether it was high vaccination rates in the environment, the agent wearing a mask or the participant themselves being masked. This pattern of

behavioral adaptation, where individuals compensate for perceived safety by engaging in riskier behaviors, emerges as an important issue to consider for pandemic management strategies (41).

It has previously been noted that risk compensation is sometimes more salient in experimental studies than in real-world tasks. Kroczek et al. (12) found that participants passed 12-20% closer to masked avatars, while Yu et al.(58) reported reduced preferred distances for both masked and vaccinated virtual agents. Laboratory experiments using the stop-distance paradigm have shown comparable results (70; 71). Aranguren et al. (70) conducted both field and VR experiments, and found risk compensation in both settings. But other large-scale observational studies, including video analyses in the Netherlands (72), sensor studies in crowded events (73), and observations in Berlin (74) have repeatedly found no evidence that mask-wearing reduced interpersonal distancing.

These divergent findings suggest that risk compensation may be amplified by cost trade-offs that are made more explicit by the studies' experimental designs. In our study, as in Kroczek's analysis (12), participants faced a clear cost-benefit calculation: maintaining distance required additional time and effort. These explicit trade-offs, while ecologically valid for understanding pedestrian scenarios, can overestimate compensation behaviors occurring in naturalistic settings where other contextual factors such as crowd density also affect individual risk calculations (72; 74; 75).

However, field studies present methodological limitations that may obscure small effects. When large-scale field studies rely on network analysis, they capture binary contact events rather than continuous distance measurements (76; 73; 77), potentially missing changes in spacing behavior. Video-based observational studies also present potential challenges with measurement precision, occlusions, and intercoder reliability when analyzing thousands of interactions (72; 75; 78). In addition, the effect sizes for risk compensation—typically a 10-20% reduction in distance—may fall within the noise threshold of these naturalistic measurements. Taken together, these limitations suggest that, while risk compensation may indeed occur in real-world settings, detecting such subtle behavioral adjustments requires controlled conditions that are only achievable in the laboratory.

From a policy perspective, policymakers should acknowledge this tendency and calibrate guidelines accordingly, perhaps by recommending slightly conservative distances or combining multiple interventions to maintain overall protection levels even if partial compensation occurs. Fortunately, risk compensation effects have been found to be too small to fully compensate for the protective benefits of social distancing (70).

5.5 Limitations

This study used a controlled laboratory setting using virtual reality, which presents both limitations and strengths. As mentioned, laboratory and VR studies sometimes show stronger risk compensation effects than field observations (70; 12), potentially due to demand characteristics. The risk compensation we observed might be less evident in the real world, where other factors such as crowd density are more salient (72; 79).

However, VR also has advantages. The enhanced experimental control it affords may reveal real behavioral patterns that are difficult to detect due to measurement noise in field studies. As discussed earlier, many large-scale observational studies face constraints, such as using binary contact measurements rather than continuous distance assessments, that may obscure small compensatory effects (76; 73; 77). In contrast, our controlled conditions allowed us to detect these small behavioral adjustments. Future researchers could make additional efforts to disguise the real goals of such studies to minimize demand characteristics while maintaining the advantages of controlled environments.

6 CONCLUSION

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Our findings demonstrate that understanding social navigation during a pandemic requires a multifactorial approach that takes into account both NPIs and environmental knowledge. As navigation decisions unfold, they are dominated by a sequence of distinct factors: initial path selection is primarily influenced by the agent's mask status, but interpersonal distance is subsequently calibrated by perception of environmental safety. This sequential view of social navigation represents a novel perspective on how people navigate risky environments.

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Our data on clearance were best explained by a three-factor additive model, with environmental safety, agent mask status, and participant mask status making independent significant contributions. Although the magnitude of these effects differed, all three factors were necessary to fully account for observed behaviors. This confirms that considering any single factor alone would provide an incomplete understanding of pandemic-related social navigation (15; 14)

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We found consistent evidence for risk compensation, with participants maintaining shorter distances in all conditions perceived as safer. This finding has implications for public policy that should be taken into account in the design of public spaces (80). For example, recommendations for interpersonal distance could be increased in anticipation of compensatory reductions, and the public could be encouraged to maintain vigilance even when protective measures are in place (41).

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In anticipation of future health emergencies, it is important to understand these behavioral consequences of new policies. Imposition of lockdowns remains challenging due to their significant social and financial costs (26; 7), making effective crowd management in public spaces essential (81). Future research should continue to explore how these multifactorial influences evolve over time and how public health communication can best account for the human tendency toward risk compensation while maintaining effective protection levels.

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