Empirical Study of Individual Evacuation Decision-making in Fire Accidents: Evacuate Intention and Herding Effect

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ABSTRACT

People's decision of evacuating or not could greatly influence the final losses in fire accidents. In order to study people's response under emergent occasions, a fire accident evacuation drill experiment was conducted in an office building without advance notice. 113 Participants' response and their decision-making process were collected by questionnaire survey right after the experiment. In this study, we mainly focused on two aspects of people's response, including participants' evacuate intention and their herding tendency during evacuate decision-making. It is found that the classical Expected Utility Theory (EUT) has certain limitation in explaining individual's evacuation intention, but the relationship between the expected utility and the evacuation intention could be represented with a modified model based on EUT. Furthermore, the herding tendency is found to be different for the two groups of people who intend to evacuate and not to evacuate. People who firstly intend not to evacuate are more easily to form herding behavior and change their minds to evacuate. Based on these findings, models of individual evacuation intention and herding tendency for two groups of people are put forward. Simulation is conducted to investigate the effect of these two changes in people's evacuation decision-making process, and results show that they both increase the final evacuation rate, reflecting the majority's risk aversion characteristics.

Keywords

Fire Accidents, Evacuation Experiment, Evacuate Intention, Herding Behaviors.

INTRODUCTION

It has been recognized that the bursts of emergencies, like earthquakes and fire hazards, are more and more frequent in recent years, and they also resulted in great losses every year. Thanks to the development of the emergency detection technology and early warning technology, it is possible to detect the emergency and disseminate the warning alarms to target crowds before the emergency creates great losses or even before the emergency really happens. Corresponding to the development of the authority's warning processes, the response of the public after they receive the warnings should also be studied and improved.

According to Lindell and Perry's Protective Action Decision Model, people's response processes include predecision process, protective action decision making and behavioral response. We could roughly combine the first two processes into one process, so the emergent response processes include decision-making process and the action taking process (Lindell and Perry, 2012). These two processes interact with each other that people's each action is decided by their decision-making process while the result of their action could create new problems for them to make decisions. By now there are a mass of research focusing on the action taking process, including problems related to movement speed, faster is slower effect, route choice, and architectural-imposed features

(Helbing et al., 2000; Haghani and Sarvi, 2016; Ma et al., 2017; Ronchi et al., 2018). And in this paper we mainly focus on the decision-making process, specifically, how people make their evacuation decisions when facing emergencies, and how other people's decision influences their own decision.

Since the middle of last century, the behavioral decision theory is the mainstream to explain people's decision-making process theoretically and many research have applied it to explain individual's consuming behavior, investing behavior, government decision-making behavior, people's emergency response and many other decision-making problems (Prather and Middleton, 2006; O'Hare and Smitheram, 1995; Stahl and Harrell, 1981; Maguire and Albright, 2005; Fischhoff, 2010). One of the most flourishing theory is the Expected Utility Theory (EUT), which explains how people behave themselves with rational sense under uncertainty conditions (Neumann and Morgenstern, 1944), and many empirical experiments have proved its feasibility and rationality (Smidts, 2000, Hu, et al., 2012; Pettigrew, 2016), most of which are in economics and financial fields, though some phenomenon, like the Allais Paradox, Ellsberg Paradox and the transitivity problem in reality could not be perfectly explained by this theory. In order to make the expected utility theory more fit into our real life and fix the paradoxes mentioned above, some assumptions in expected utility theory were loosened, like the linear feature and transitivity hypothesis, generating models like the Regret Model (Loomes and Sugden, 1982).

It is also widely acknowledged that individual's decision could be influenced by others opinions to some extent. This influence has been continuously studied by psychologists and sociologists, and among them the herding behavior is one of the hot issues. By now the herding behaviors have been found in a number of areas and most of them lie in the field of economics and finance. A few of them put their eyes on the field of emergent occasions, proving the existence of herding behaviors during emergencies (Altshuler, et al., 2005; Wei, et al., 2014). Recent years researchers started to investigate herding properties under emergent occasions. Some attempted to discover the depending factors of herding behaviors, including environmental and personal factors (Lovreglio, et al., 2016). Some endeavored to look into the condition of the appearance of herding behaviors, like the individual interaction level and uncertainty level (Chang, 2014; Haghani and Sarvi, 2017). Different qualitative and quantitative models were brought up based on these findings, including sequential decision model (Banerjee, 1992; Morone, 2012), informational herding model (Cipriani and Guarino, 2014), and an asymmetric information and Bayesian learning model (Hott, 2009).

In summary, the Expected Utility Theory and its modified theories are good methods to explain people's decision-making results, but how it could be applied in the condition of people's evacuation decision-making in emergencies is still needed to be studied further. On the other hand, the overall generation process and causes of herding behaviors, and its characteristics and consequences under different conditions also remain unknown to us all. In order to verify the applicability of EUT to people's individual evacuation decision-making, and to investigate the herding properties under emergent occasions, a fire hazard evacuation drill experiment was conducted and analyzed.

EXPERIMENT DESIGN

The experiment was conducted on December 20, 2018 in Liuqing Building, which is an eleven-storey office building of Tsinghua university, China. The objects of this fire hazard evacuation drill were all graduate students who had been working in this office building for more than half years. At about 4.30 p.m., the central control room of this building issued a fire alarm with explanation "There is a fire accident on the sixth floor of this building. Please evacuate immediately" without advance notice. It was worth mentioning that the sixth floor was being decorated and was vulnerable for fire disasters during those days, this fire alarm was reasonable and believable. All students were told that it was an evacuation drill only after they evacuated out of the building.

Figure 1. Evacuating Scene in the Experiment

After the evacuation drill, a questionnaire was given out to the students in this building in order to collect their experiment psychology and behaviors during evacuation. Totally 116 people replied the questionnaire, but 3 of them were invalid because they did not participate in the experiment.

EVACUATE INTENTION ANALYSIS

The main points of this research are the individual evacuation decision and herding behaviors. The individual evacuation decision is studied based on the expected utility theory. Totally 76 people intended to evacuate in the very beginning without being influenced by other people, and 37 people intended not.

The following table describes the payoff matrix of each individual choosing to evacuate and not evacuate under the circumstances of true alarm and false alarm (Table 1). The variable *a, b, c, d* respectively represents people's gains or losses when the warning is true or false.

Table 1. Payoff Matrix of Evacuation Intention

Payoff	True	False
Evacuate	a_i	b_i
Not evacuate	c_i	d_i

Since the losses of evacuating should be smaller than that of not evacuating if the alarm is true, it should be tenable that $b > a$. For similar reason, we can get $c > d$. So the following condition is employed in order to exclude invalid respondents:

$$b - a \geq -1 \quad (1)$$

$$c - d \geq -1 \quad (2)$$

So the number of final effective samples decreases to 93.

In this questionnaire the variable *p, a, b, c*, and *d* were acquired by a set of quantitative evaluation questions. The distribution is presented below (Figure 2 and 3). A positive result is that more than half of the respondents considered the warning reliability to be higher than 80%, which is in favor of the whole evacuation process management. As for the payoff variables, the variable of *b* and *d* are clear that most people's evaluation on their losses if they did not evacuate was relatively concordant that most of them considered that if there was a fire and they did not evacuate, their losses would be very high. If there wasn't a fire and they did not evacuate, their losses would be very low. This result was reasonable and appropriate to our common sense. While for the condition that people chose to evacuate, no matter the warning was true or false, people's evaluation on their losses were quite different that almost all zero to ten scores were occupied by several respondents, and broadly the perceived losses of condition of true warning was slightly higher than that of the condition or false warning. The general comparison of the average number is: b > a > c > d, which is consistent with the assumption of Equation (1) and (2).

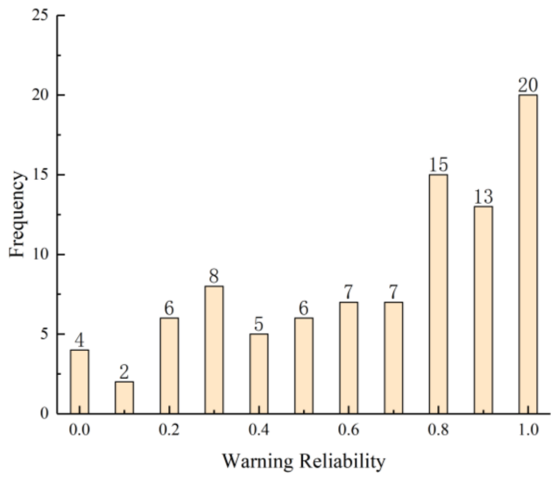

Figure 2. Distribution of Reliability Evaluation

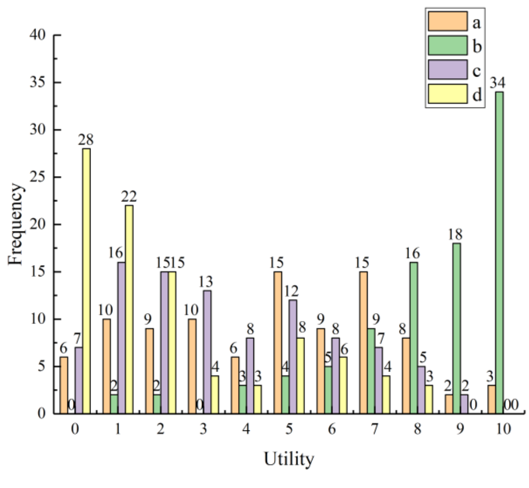

Figure 3. Distribution of Loss Evaluation

According to the expected utility theory, the expected utility function is given by

$$U = p_1 u(x_1) + p_2 u(x_2) \quad (3)$$

Let $p_i (0 \le p_i \le 1)$ be the perceived probability of emergency happening of individual i, which means their perceived warning reliability. So the utility function of each individual i is given by

$$U_i(evacuate) = p_i a_i + (1 - p_i) b_i , \quad (4)$$

$$U_i(not - evacuate) = p_i c_i + (1 - p_i) d_i . \quad (5)$$

So the final expected utility should be

$$U_i = U_i(evacuate) - U_i(not - evacuate) \quad (6)$$

Theoretically, people's individual decision on evacuating or not is decided by the expected utility:

$$y_i = \begin{cases} 1(evacuate) & U_i > 0 \\ 0(not - evacute) & U_i \le 0 \end{cases} \quad (7)$$

According to the expected utility and their evacuation intention, we classify these respondents into four quadrants (Figure 4). The first quadrant represents people whose expected utility is larger than 0 and intended to evacuate and the third quadrant represents people whose expected utility is smaller than 0 and intended not evacuate. The decision of these two kinds of people is consistent with their evaluation of risk, including probability and loss, which are the parts that the EUT could explain. The second quadrant represents people whose expected utility is larger than 0 while intended not to evacuate, and the fourth quadrant represents people whose expected utility is smaller than 0 but intended to evacuate. Among these four quadrants, the second and the fourth quadrants are abnormal, and they indicate the feature of risk appetite and risk averse separately. This kind of abnormal phenomenon occurs only 21% in the positive expected utility group but occurs 43% in the negative group.

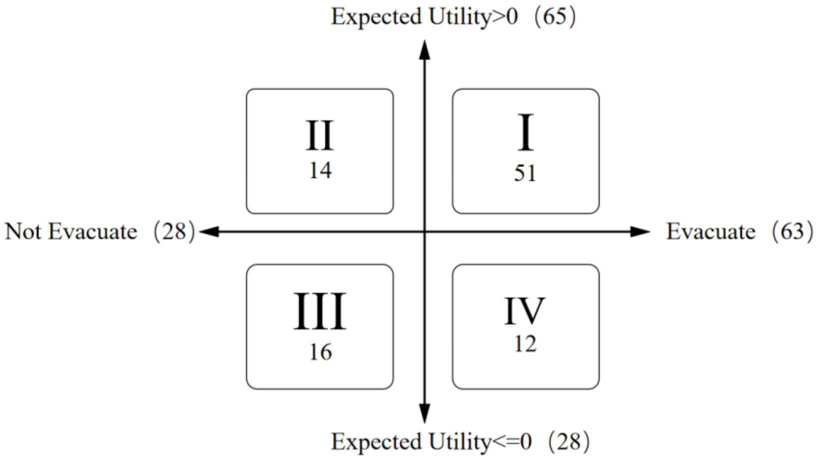

Figure 4. Four Quadrants of Expected Utility and Evacuation Intention

The probability of evacuating intention for each utility group is calculated and plotted in Figure 5. The area of the orange bubbles represents the sample numbers for each utility value. The larger the bubble is, the more samples we observe in the group. The figure shows that there is a horizontal stage when the expected utility is larger than 3, indicating that when the utility reaches to a certain level, the evacuation intention probability reaches to its limiting value 1. Considering this feature and that the probability is not linear correlated with expected utility, the EUT could not perfectly explain people's evacuation decision-making.

From the figure we can easily filter out the abnormal points whose samples are too small to reflect the reality. It is found that the remaining points could be relatively well fitting into the Boltzmann function:

$$y = A_2 + \frac{A_1 - A_2}{1 + \exp[(x - x_0)/dx]} . \quad (8)$$

Due to the missing data of very low expected utility, the result of the fitting parameters is not appropriate enough, but the shape of the curve is reasonable. The two platforms of the curve represent the two extreme values of the evacuating probability, and the progressive increasing feature in the middle expected utility section also fits well to the data. Theoretically the evacuating probability of the central position should be around 0.5, while there is an offset for the curve, indicating the risk averse feature of people's evacuating decision, which is consistent with with the results shown in Figure 4.

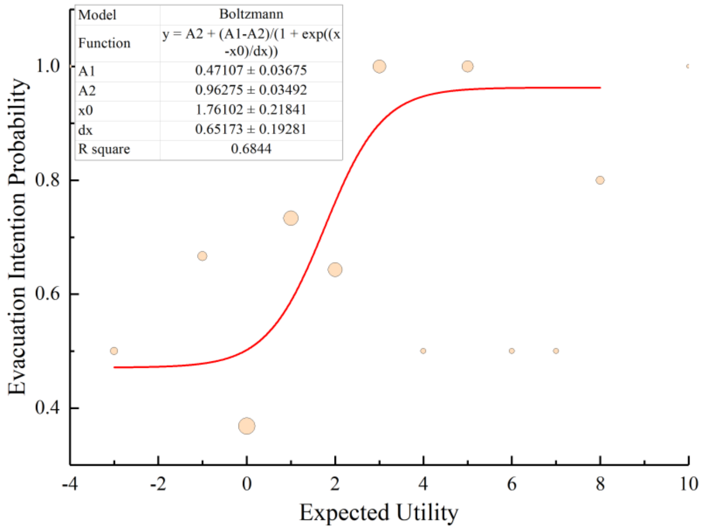

Figure 5. Relationship between Expected Utility and Evacuation Intention

Based on the above results, people's individual decision of evacuating or not largely depends on their expected utility, but partially inconsistent due to the risk averse feature and statistical errors. In order to simplify the model, the Boltzmann function is modified to a piecewise linear function, which is denoted by:

$$f(x)=\begin{cases} A & x<a \\ \dfrac{A-B}{a-b}x+\dfrac{Ab+aB}{a-b} & a\le x<b \\ B & x\ge b \end{cases} \quad (9)$$

Considering the boundary condition that $f(x_{\min})=0$, $f(x_{\max})=1$ and linear fitting result, the individual evacuating decision probability could be denoted by Formula 10 and Figure 6.

$$f(x)=\begin{cases} 0 & x<-6.2 \\ 0.09x+0.56 & -6.2\le x<4.9 \\ 1 & x\ge 4.9 \end{cases} \quad (10)$$

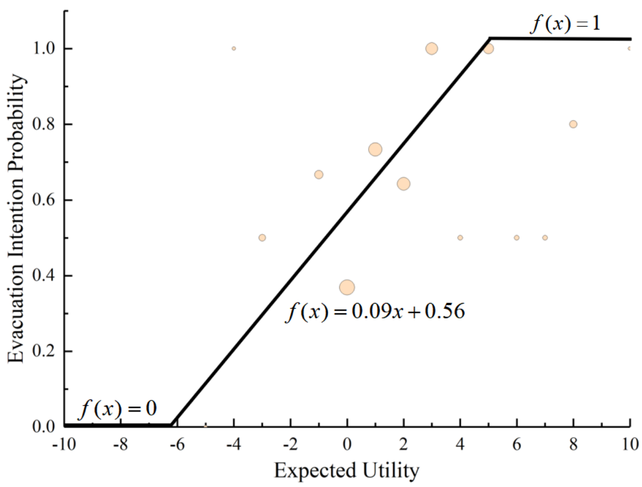

Figure 6. Model of Evacuation Decision-making

HERDING TENDENCY ANALYSIS

The herding behavior was investigated by an imaginary question. The question was “How many people deciding not to evacuate could change your mind to stay?” for people who intended to evacuate, and “How many people deciding to evacuate could change your mind to evacuate?” for people who intended not to evacuate.

Here we refer to Avery and Zemsky’s definition of herding among traders and market makers and define the herding behaviors of evacuating decision-making under emergent occasions:

Individual i is considered to have had herding behaviors in evacuate decision-making if: (i) initially he intended not to evacuate (resp. to evacuate); (ii) after knowing the condition that a certain number of people who decided to evacuate (resp. not evacuating), he changes his mind to evacuate (resp. not to evacuate).

The statistical results of the imaginary questions is shown in Figure 7. It is found that different herding patterns for these two occasions. The proportion is small for participants who intended to evacuate if they find one or two people not to evacuate. And then the proportion goes up with the number of people who decide not to evacuate going up. The proportion reaches to the peak when the number of people not to evacuate reaches to 6 to 8 people and decreases after that. The decrease tendency might be due to the limitation of total number of participants, which means if the total population is larger, the tendency would be going up continuously. In addition, almost 40% of them claimed that they would not change their minds no matter how many people decided not to evacuate.

As for people who intended not to evacuate, the tendency changed. In addition to the 16% of people who would not change their minds no matter how many people evacuating, the number of people changing minds goes down with the evacuating people going up, and over 30% of people would change their minds when there is only 1 or 2 people evacuating, three times more than people who intended to evacuate. The different tendency for people who intended to evacuate and not evacuate shows an asymmetric herding tendency for evacuation decisions.

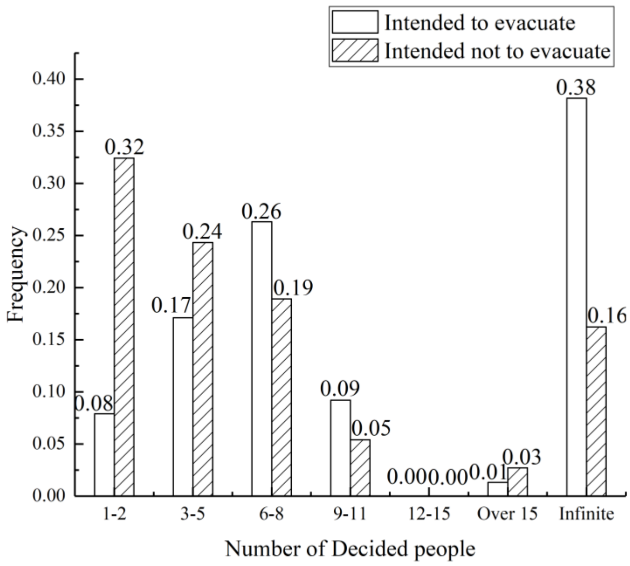

Figure 7. Answers for the Question:

“How many people deciding (not) to evacuate could change your mind?”

An assumption is that this asymmetric herding tendency arises due to the asymmetric expected utility distribution. In order to verify this assumption, we analyzed the correlation between the people’s propensity of changing minds and the difference value of their expected utility from the changing point (zero), for both two kinds of people who intended to evacuate and not evacuate. Results show that there is no significant correlation between these two variables, indicating the incorrectness of this assumption and the existence of the asymmetric herding tendency for two groups of people.

Here we use the arrays *E* and *NE* to represent the groups of people who intended to evacuate and not evacuate, and e_i and ne_i to be the individuals in *E* and *NE*: $E = \{e_1, e_2, \Lambda, e_i, \Lambda\}$, $NE = \{ne_1, ne_2, \Lambda, ne_i, \Lambda\}$.

Since the number of people who evacuating or not evacuating when people change their minds at time *t* reflects their herding tendency, we define *m(t)* as the proportion of people who decided not to evacuate at time *t*, and *n(t)* as the proportion of people who decided to evacuate at time *t*. So the probability of individual e_i changing his mind not to evacuate $f(x)(0 \le f(x) \le 1)$ is decided by *m(t)*, and the probability of individual ne_i changing his mind to evacuate $g(x)(0 \le g(x) \le 1)$ is decided by *n(t)*.

Due to the increasing derivative of *f(x)* and decreasing derivative of *g(x)*, *f(x)* and *g(x)* satisfy that:

$$f''(m(t)) \ge 0,\ g''(n(t)) \le 0. \tag{11}$$

According to the experiment results, for people who intended not to evacuate, there are about 16% of them claiming not changing their minds. And for people who intended to evacuate, there are even more people not changing their minds. So the boundary condition is denoted by:

$$f(0) = 0, g(0) = 0, \tag{12}$$

and

$$f(1) = f_{\inf}, g(1) = g_{\inf}, \text{ where } f_{\inf} < g_{\inf}. \tag{13}$$

So the herding tendency for people who intended to evacuate and not evacuate is shown in Figure 8.

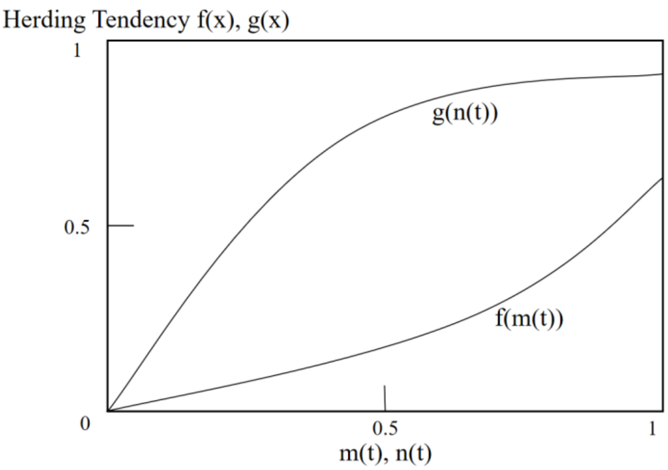

Figure 8. Model of Herding Tendency

According to the questionnaire result, people's herding tendency have a good fit of goodness over 0.99 with quadratic function (Figure 9), and the quadratic function also fits well with the characteristics of herding tendency mentioned above. The function is:

$$f(m) = 0.004m^2 + 0.028m, \tag{14}$$

$$g(n) = -0.008n^2 + 0.153n. \tag{15}$$

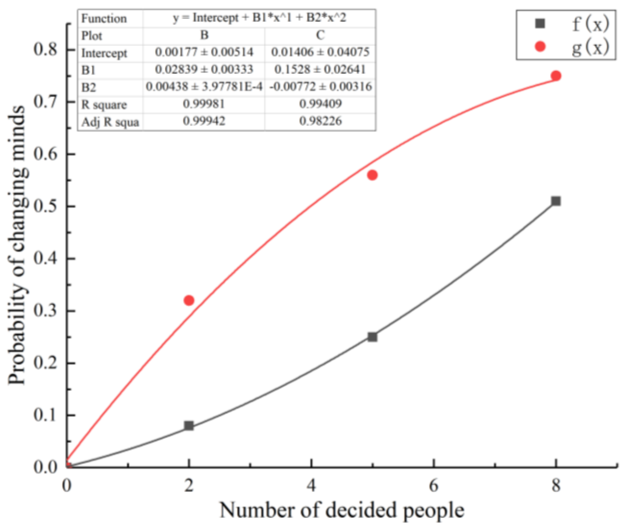

Figure 9. Fitting Result of the Herding Tendency Model

EFFECT OF THE EVACUATION INTENTION MODEL AND THE ASYMMETRIC HERDING MODEL

In order to evaluate the effect of the different individual decision model and different herding tendency for two groups of people, a simulation is conducted on Netlogo 5.3.1. Considering that the average number of people in a room in this experiment is 10 people, the population was set to be 10 in each simulation. Multiple simulation (10 000) is conducted for each setting in order to eliminate the effect of statistical error and get a stable result.

Figure 10 shows the evacuation rate using the original expected utility theory and the modified piecewise function for individuals' evacuation decision making. The conformity level was set to be zero in order to eliminate the influence of herding. The curve for the expected utility theory is a linear function, which is consistent with our simulation setting. As for the curve for the evacuation intention curve, it is found to be a little shifted towards the left side, indicating the risk averse property of the majority. The two ends of the curve create two horizontal stages, reflecting the existence of thresholds of expected utility for 100% probability of deciding to evacuate or not evacuate, which is consistent with our findings in Section 3: Evacuate intention analysis.

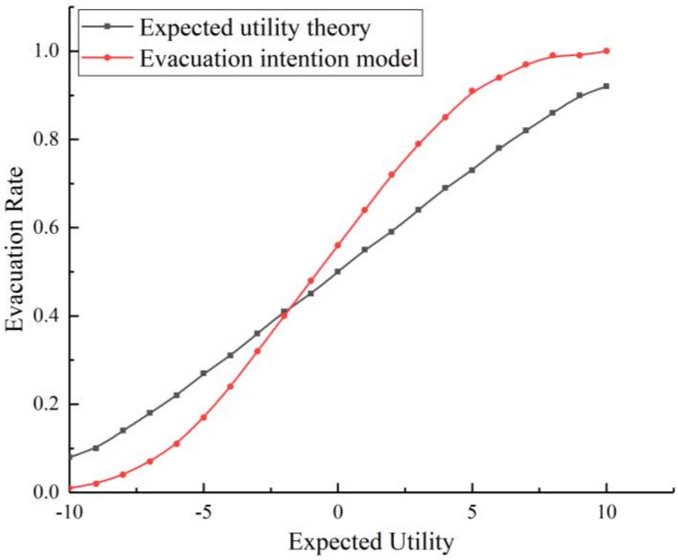

Figure 10. Effect of the Evacuation Intention Model

Figure 11 shows the different evacuation rate for different herding modes. The linear herding mode means that people's herding tendency is linearly dependent on the number of people equally for both people who intend to evacuate and not to evacuate. The asymmetric herding curve shows the relationship between people's expected utility and their final evacuation rate if their herding tendency is non-linear with the number of people deciding to evacuate or not, like the result in Section 4: Herding tendency analysis. The simulation result of the asymmetric herding curve is also a little shifted towards the left side, also indicating the majority's risk aversion property.

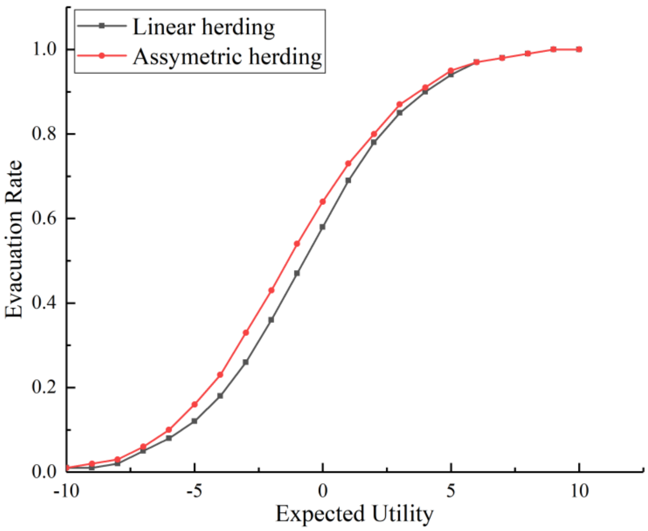

Figure 11. Effect of the Herding Tendency Model

CONCLUSIONS

In order to look into people's evacuation decision under emergent occasions, an evacuation drill experiment was conducted and the related data was collected by the method of questionnaire survey.

According to the experiment results, the probability of evacuation intention is not linearly correlated with the expected utility, indicating the limitation of Expected Utility Theory in explaining individual's evacuation decision-making in emergencies. The whole distribution of their evacuation intention reveals a propensity on evacuating under emergent occasions. Two thresholds are found to keep the evacuation rate staying the value of 0 or 1. Based on these findings, a modified version of the expected utility theory applied to the occasion of individual evacuation decision-making, which uses the form of piecewise function, is brought up.

Another finding is that the herding tendency of the two groups of people who intended to evacuate and not evacuate presents different modes. Compared with people who intended to evacuate, people who intended not to evacuate are more easily influenced by others to change their minds to evacuate, showing stronger herding tendency. Thus a model describing this asymmetric herding tendency is brought up.

Based on the two models mentioned above, a simulation is conducted to investigate the effect of these two changes in people's evacuation decision-making process, respectively the changes of the individual decision-making model and the asymmetric herding tendency for the two groups of people. The offset of the individual decision-making curve and the higher evacuation rate of the curve of asymmetric herding tendency both reflect the risk aversion property of the whole crowds.

In order to improve the validity of this study, more experiments should be conducted to acquire larger sample size. Besides, some questions are found in this research: is there any other factor that could exert influence on people's evacuation intention except the payoff evaluation discussed in this research? How do people's herding tendency change when the total population gets larger? These questions would also be answered in the future study.

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