Stress Dynamics in Evacuations: A Vicsek Model Simulation Approach

Clara Berglund Hiltunen, Emil Erlingstam, Sofia Källhammer, Filip Olsson, Alexander Ybring
Chalmers University of Technology

ABSTRACT

This project delves into the dynamics of building evacuations through agent-based simulation, utilizing the Vicsek model. The study addresses the critical relationship between evacuation time, stress levels, and the number of individuals, challenging conventional assumptions such as the faster-is-slower effect and Yerkes-Dodson's Law. Surprisingly, the simulations reveal that higher stress levels lead to shorter evacuation times independent of the number of individuals, contrary to traditional expectations.

The simulation model incorporates nuanced factors, including stress-induced changes in decision-making, clustering effects, and cognitive impacts on evacuation dynamics. The study conducts a short analysis, exploring the interplay of these elements in emergency scenarios. Notably, the findings emphasize the intricate nature of stress dynamics during evacuations, highlighting the need for further research.

Recommendations for future work include fine-tuning simulation parameters to better align with real-world scenarios, as well as simulating even higher stress levels and more realistic building layouts. Adjustments such as optimizing stress levels, refining clustering factors, and setting chaos thresholds aim to enhance the model's accuracy and predictive capabilities. This research contributes valuable insights to the refinement of building safety protocols, ultimately elevating the effectiveness of emergency evacuations.

I. BACKGROUND

The safety and efficiency of building evacuations are critical aspects of emergency preparedness, and understanding how stress influences evacuation times is crucial for optimizing evacuation strategies. The urgency creates an increase of stress that could potentially cause irrational decision making and congestion at bottleneck sites such as doorways and hallways [1].

In fact, there is an effect, called faster is slower-effect, describing this scenario. When a crowd is evacuating an area, some individuals in the crowd are trying to move towards the exit at a higher velocity than the rest of the crowd, which may result in clogging. This may cause individuals to push to escape faster which in turn results in an even longer evacuation time. [2].

However, although the urgency of evacuating a potential hazardous situation increases the stress level [1], the so called Yerkes-Dodson's Law states that there is a optimal level of stress, at which the performance is at its best. A moderate level of stress makes the crowd aware of the situation and can potentially benefit their ability to act both smart and fast. If the level of stress goes significantly below this optimum there is a risk that people do not realize how hazardous the situation is, which could lead to awful consequences. On the other hand, a stress level higher than this optimum could cause irrational decision making and chaos. Both scenarios decrease the performance [3]. The relation between stress and performance according to Yerkes-Dodson's Law is shown in Figure 1.

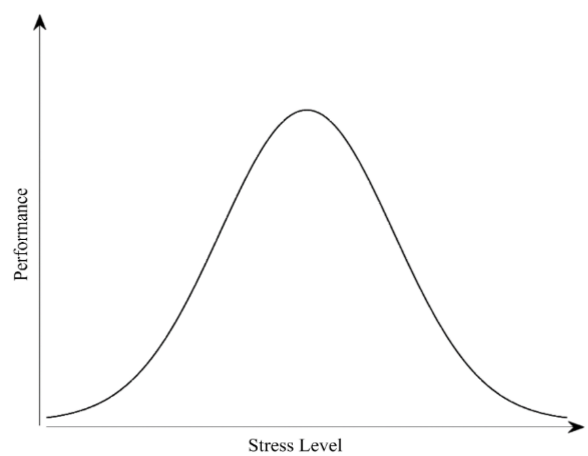

Figure 1. *Illustration of the Yerkes-Dodson's Law: relation between stress level and performance. Moderate stress level leads to the best possible performance.*

Therefore, in this research project, we aim to comprehensively analyze the evacuation dynamics of a building during emergency scenarios, specifically focusing on the interplay between evacuation time, individual stress levels, and the total number of occupants. We propose to conduct simulations that aim to replicate real-world evacuation scenarios, taking into account varying stress levels experienced by individuals during emergency situations. By utilizing simulations in Python we intend to quantify the impact poor decision-making and movement patterns during evacuation. Additionally, we will investigate the correlation between evacuation time and the total number of individuals present in the virtual building layout. The outcomes of this research could not only contribute to the improvement of building safety protocols, but also provide valuable insights for designing interventions that can mitigate stress and enhance the overall effectiveness of emergency evacuations.

Questions

- How does stress and the number of individuals affect evacuation time?
- What factors should be included in the simulation model to accurately represent real-world scenarios?

II. METHOD

A. Simulation architecture

The simulation takes place in a square layout consisting of four rooms separated by walls forming a cross when seen from above, as seen in Figure 2. Movement between the rooms are only possible through the doorways located between the inner cross-forming walls and the outer walls, giving each room a doorway to its two neighbouring rooms. The two exits are situated in the middle of the upper and right outer walls, meaning that in order to escape from the lower left room, either upper left or the lower right room have to be traversed.

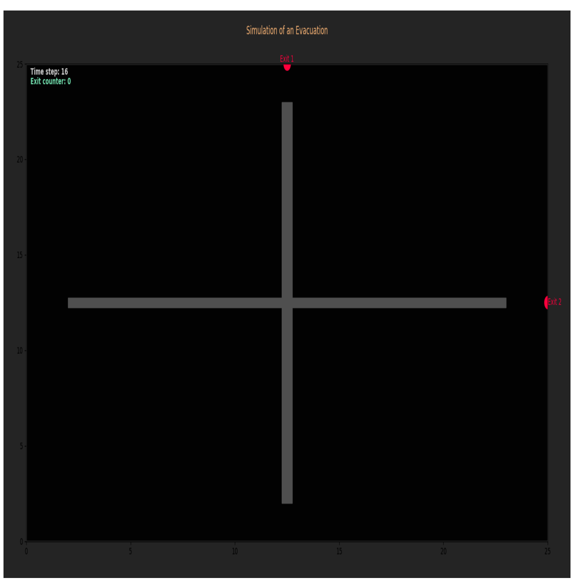

Figure 2. *The virtual layout in which the simulation takes place. Exits are marked with a filled semicircle on the top and left walls. Individuals must navigate around the cross representing walls to reach one of the exits.*

B. Simulation model

The simulation proceeds in discrete time steps. During every simulation the there will be a noise term corresponding to the stress level of the individuals, η. This term will be equal for all individuals in a simulation run, but every simulated individual will also have the following attributes: an angle of movement, θ, a speed v and position coordinates $\mathbf{r} = (x, y)$, all of which influence their movement of the individuals.

During initialization, the orientations of the individuals are randomly assigned between 0 and 2π and the coordinates are randomly assigned with the limitation that the individuals are evenly distributed between the four rooms. The initial speed of each individual is randomly chosen from a Gaussian distribution with a mean proportional to the stress-level. The variance was kept constant to ensure realistic speeds.

The Vicsek model is a type of self-propelled particle model that can be used to describe swarm-like behaviour [4]. The individuals' orientation of movement is influenced by other individuals close to them. Thus, a visibility sphere with flocking radius R_f, is implemented such that individuals within the sphere, with index k, of individual j satisfy the following equation

$$|\mathbf{r_k} - \mathbf{r_j}| < R_f. \tag{1}$$

An illustration of the visibility sphere application is shown in figure 3.

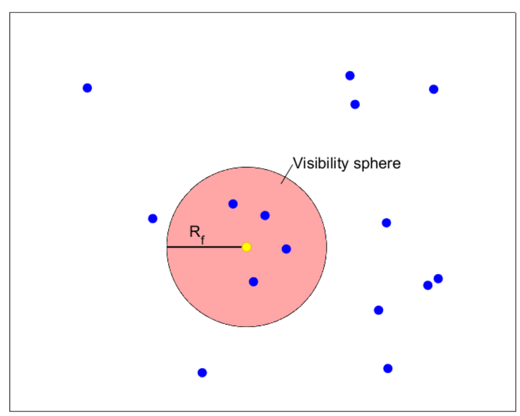

Figure 3. *Illustration of visibility circle (red) of individual j (yellow). The four blue individuals within the visibility sphere will influence the mean angle of movement of the yellow individual according to equation (2).*

Furthermore, the mean angle of movement of the individuals within the visibility sphere at time step n is calculated using the circular mean as follows

$$\langle\theta_{k,n}\rangle = arctan\left[\frac{\langle sin(\theta_{k,n})\rangle}{\langle cos(\theta_{k,n})\rangle}\right]. \quad (2)$$

Note that individual j is included in the mean angle calculation.

In the simulation, the angle of movement of an individual is influenced by $\langle\theta_{k,n}\rangle$, the angle of movement at the previous time step as well as the direction of the closest exit relative the position of the individual, $\varphi_{closest\ exit}$. Thus, the angle of movement of an individual j at time step n can be expressed as

$$\begin{aligned}\theta_{j,n} = w_1\left[(1-w_2)\theta_{j,n-1} + w_2\langle\theta_{k,n-1}\rangle)\right] + \\ +(1-w_1)\varphi_{closest\ exit}.\end{aligned} \quad (3)$$

w_1 and w_2 weight the impact of $\theta_{j,n}$, $\langle\theta_{k,n}\rangle$ and $\varphi_{closest\ exit}$ on the updated angle of movement. In this model $w_1 = w_2 = 0.5$, resulting in equal contributions from $\theta_{j,n}$ and $\langle\theta_{k,n}\rangle$, whereas the impact of $\varphi_{closest\ exit}$ is greater. This weighting causes the individuals to towards the exits and thereby evacuate the layout.

However, in order to use equation (3), $\varphi_{closest\ exit}$ has to be calculated. To begin with, the closest exit relative a individuals position is obtained by using the Euclidean distance

$$d_j = \sqrt{(x_{exit} - x_j)^2 + (y_{exit} - y_j)^2} \quad (4)$$

where d_j is the straight-line distance between an exit and an individual j. Then, the direction of the closest exit is calculated according to

$$\varphi_{closest\ exit} = arctan\left[\frac{y_{closest\ exit}/y_j}{x_{closest\ exit}/x_j}\right]. \quad (5)$$

Moreover, research shows that acute stress can affect the executive functions of the brain [5]. Among these functions are planning, organizing and impulse control, all of which play an important role in an evacuation scenario. Therefore, a feature where an individual changes direction and moves towards the second closest exit was implemented by substituting $\varphi_{closest\ exit}$ with $\varphi_{2^{nd}\ closest\ exit}$,

$$\varphi_{2^{nd}\ closest\ exit} = arctan\left[\frac{y_{2^{nd}\ closest\ exit}/y_j}{x_{2^{nd}\ closest\ exit}/x_j}\right] \quad (6)$$

in equation (3). This would only happen if an individual's speed is above a threshold, meaning stressed individuals are more likely to be confused. After a while, the individual would then change direction back to its original closest exit.

If an individual change direction as described above, it will affect the angle of movement of the individuals within its visibility sphere, subsequently changing their angle of movement. This is caused by the fact that $\theta_{j,n+1}$ in equation (3) depends on the mean angle of movement, which in turn is calculated using the angle of movement of the individuals in the visibility sphere. Thus, the simulation consider how one individual can confuse others and cause them to second guess their choice of direction.

In addition to angle of movement, the speed of an individual may also be affected by neighbouring individuals. Due to the fact that several individuals will be moving in roughly the same direction but at different speed, potential clusters of individuals will form as some catch up and others get caught up. To determine if a cluster really has been formed, the following equation

$$|\mathbf{r_l} - \mathbf{r_m}| < T. \quad (7)$$

where T is the threshold value and $l \neq m$, is used. If an individual satisfy equation (7) relative at least one other individual, it is a part of the cluster. Considering this, a cluster can consist of two or more individuals. An example of how a cluster might look like is shown in figure 4.

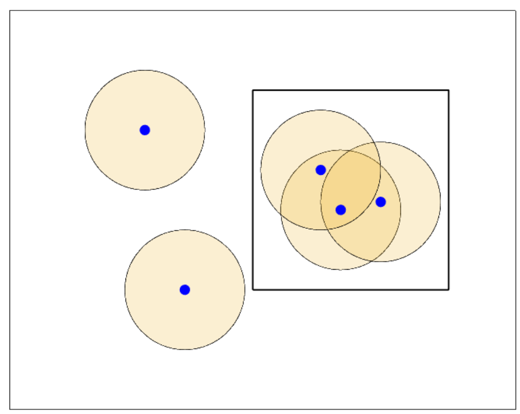

Figure 4. *Illustration of a cluster among five individuals (blue dots). The yellow circles, with radius T, illustrates the proximity another individual has to be within in order for the them to form a cluster. The three individuals encircled by the box make up a cluster since every individual is at least within the circle of another individual. The other individuals are not a part of the cluster.*

In a cluster, the speed of the individuals will be reduced by some factor in order to simulate bottlenecks and limitation in movement speed that may occur in crowds. However, since the speed of individuals before entering the cluster were different, their reduced speeds are so too, meaning by moving scientifically faster or slower, an individual can get out of a cluster.

Using the speed and the angle of movement of an individual j, its velocity at time step n, $\mathbf{v_{j,n}}$, can be calculated as follows

$$\mathbf{v}_{j,n} = v_{j,n}(cos(\theta_{j,n})\hat{\mathbf{x}} + sin(\theta_{j,n})\hat{\mathbf{y}}) \tag{8}$$

where $v_{j,n}$ is the speed of individual j at time step n. Using the velocity vector, the coordinates for individual j at time step $n+1$ is then calculated according to

$$\mathbf{r}_{j,n+1} = \mathbf{r}_{j,n} + \mathbf{v}_{j,n}\Delta t \tag{9}$$

where Δt is the time step length, which is set to 1 in this simulation model.

C. Execution of simulation model

For different executions of the simulation model, the number of individuals, N, and stress level varied. The number of individuals ranged from 10 to 110 by increments of 10. The stress level varied between 0.05 and 0.175 and was evenly spaced by increments of 0.025. Every combination of number of individuals and stress level were simulated five times, giving a total of 330 simulations.

In every simulation, the individuals will be initialized as described in II B. *Simulation model*. An example of what this might look like is shown in figure 5. Note that the individuals are distributed in the entire layout. Once the virtual fire alarm has gone off, the individuals will start moving and evacuating the layout. This time step marks the start of the evacuation. At every subsequent time steps, the attributes of the individuals will be updated in accordance with the simulation model described in II B.

At a later stage in the simulation, some of the individuals have passed an emergency exit and others are on their way to one of the two emergency exits. This scenario is shown in figure 6. The simulation goes on until all individuals have evacuated through either of the two exits. The number of time elapsed from the activation of the alarm to the final individual leaving the layout, i.e. the escape time, will noted.

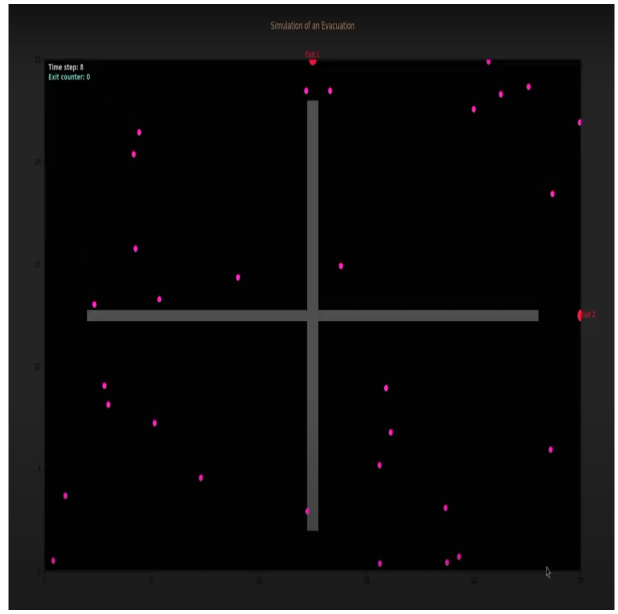

Figure 5. *The simulation before the fire alarm is turned on. The individuals (pink dots) are evenly distributed in the layout and are stationary.*

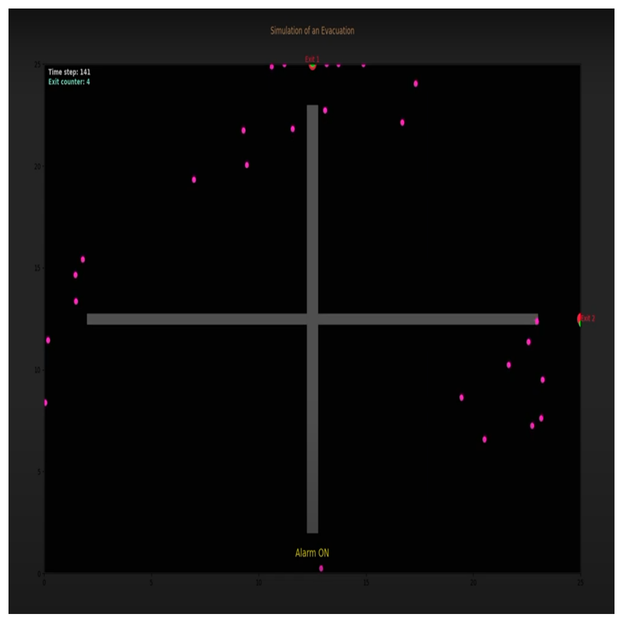

Figure 6. *The simulation 140 time steps after the start of the evacuation. The individuals (pink dots) move towards the exits, (red semicircles) without intersecting the walls (gray cross).*

III. RESULTS

To generate the results, the simulation was executed as described in section II C. Figure 7 shows the escape time as a function of N, and that the mean evacuation time increases with the number of individuals. Also, with more individuals in the room, the variance in the escape time decreased.

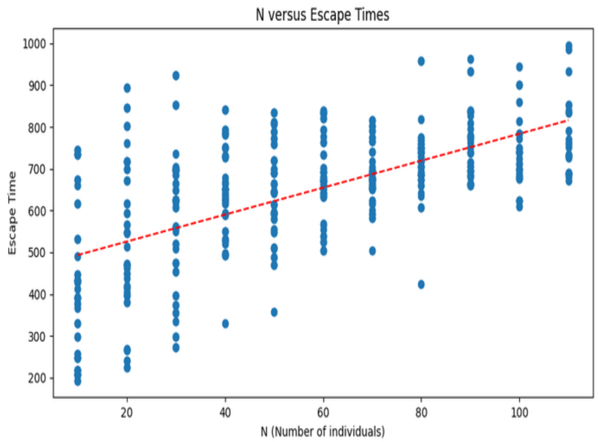

Figure 7. *Escape time in number of time steps as a function of the number of individuals. The red dashed line is a linear regression of the data points. In these runs, all simulated values for the stress level η are included.*

The escape time statistics using different number of individuals are summarized in table I. In the calculation of the mean, variance and standard deviation, all simulated values of η were included. The standard deviation of escape time shows a decreasing trend as N is increased. With increasing number of individuals, the mean escape time also increases.

Table I. *Escape time statistics for various population sizes (N).*

N	MEAN	VAR	STD
10	409.3	32341.7	179.8
20	525.2	33367.1	182.7
30	578.9	25444.9	159.5
40	645.2	11240.1	106.0
50	647.2	11665.7	108.0
60	681.8	8457.0	92.0
70	683.5	4449.6	66.7
80	718.4	6358.0	79.7
90	753.5	6523.7	80.8
100	734.4	6988.7	83.6
110	776.1	8723.4	93.4

Figure 8 shows the escape time as a function of stress level. The linear regression shows that a larger value of η results in a lower mean evacuation time. The variance however remains of similar size.

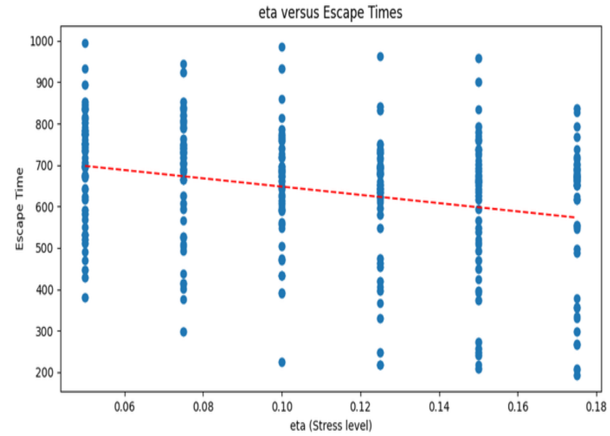

Figure 8. *Escape time in number of time steps as a function of the stress level of the individuals. The red dashed line is a linear regression of the data points. In these runs, all simulated number of individuals are included.*

Table II summarizes the statistics of the escape time using different stress levels. In the calculation of the mean, variance and standard deviation, all simulated values of N were included.

Table II. *Escape time statistics for different stress levels (η).*

η	MEAN	VAR	STD
0.05	695.4	17159.0	131.0
0.075	690.0	19171.7	138.5
0.1	639.4	18570.8	136.3
0.125	612.0	23205.4	152.3
0.15	590.5	34157.7	184.8
0.175	586.0	29484.5	171.7

In Figure 9, the total evacuation time was plotted against the number of individuals and stress level. The trend line for this data set is shown in Figure 10. This figure shows that a small number of individuals and a high level of stress results in the shortest possible evacuation time, since the plane has its minimum in the back corner. From the linear regression plane in figure 10, one can also conclude that N has a greater impact on the escape time compared to η.

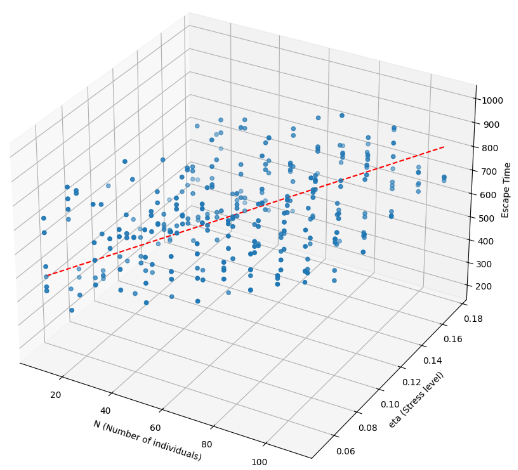

Figure 9. *Escape time in number of time steps as a function of the number of individuals and stress level. The red dashed line is a linear regression of the data points.*

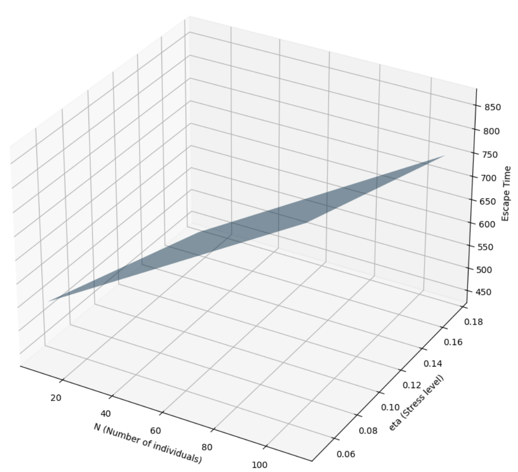

Figure 10. *Linear regression of the escape time as a function of the number of individuals and the stress level. The minimal evacuation time is found in the back corner, corresponding to low N and high η.*

IV. DISCUSSION

The result from the simulation shows that the evacuation time is shorter for a higher level of stress and a lower number of individuals. This can be due to that the initial speed of the individuals are proportional to the stress level and that there are fewer individuals, resulting in less clusters forming, meaning few individuals get a reduced speed.

On the other hand, a higher number of individuals and a lower stress level result in longer escape times. The primary cause of this when the number of individuals are high is the clusters that appear, decreasing the speeds of the individuals drastically. For a higher number of individuals, more clusters appear resulting in the evacuation taking longer time. When it comes to the stress level being low, a possible explanation is lower initial speeds.

Furthermore, the clusters that appear when the number of individuals is higher are also a potential explanation for why the the variance in the escape time is smaller for higher number of individuals, as seen in table I. With low speeds, as in a cluster, there are no highly stressed individuals that change direction. And there is overall less chaos, resulting in more consistent escape times.

However, in table II, the variance in escape time is rather big for both low and high values of stress, η, suggesting that η has a weaker influence on escape time compared to N. This can be due to η having both negative and positive effects on escape time, since a higher stress level means faster movement, but also that the individuals have a higher probability of changing direction.

The result of the relation between stress and evacuation time goes against both the faster-is-slower effect and the Yerkes-Dodson's law. If the result of the simulation was in line with the faster-is-slower effect, the evacuation time would be longer for very high values of η. However, if the Yerkes-Dodson's law was applied, the escape time would be at its lowest level for a moderate level of stress, which is neither the case.

The escape time is more dependent on the number of people in the room than their stress levels. Probably, adding higher stress levels in the simulation set is needed to see the full expected result of the relation between stress level and escape time. As mentioned in section I, stress levels higher than the optimal stress level could result in chaos and makes the individuals move in random directions. When chaos occurs, the evacuation time increases rapidly. In this simulation, stress has both positive and negative effects, increasing individuals' speeds, but also increasing congestion and chaos. In this simulation the pros seemed to outweigh the cons of higher stress levels.

V. CONCLUSION

To conclude, an agent based simulation is an effective way of modelling complex phenomena such as stress dynamics in evacuation scenarios. Stress influences the escape times drastically, which is also evident in the simulation. For the simulated evacuation scenarios, escape time was minimized with few individuals and high stress levels. Surprisingly, increasing stress levels shortened the escape time even if the room was fully occupied, challenging the assumption of the faster-is-slower effect and Yerkes-Dodson's Law.

By implementing varying speeds, clustering and chaos, a simulation model can be used to predict the escape time for different number of individuals and stress levels. To further increase the complexity of the simulation and better represent real-world scenarios, higher stress levels need to be simulated without increasing individuals' speeds to unrealistic levels. Implementing a maximal allowed speed could be a practical approach in this regard. When the stress level is high enough so that the maximum speed is reached, further increasing stress would only have negative effects. Even though the model's simplifications, the correlation between the number of individuals and stress level is clearly present. This emphasizes the potential for further development to enhance the predictive capabilities. Further work on fine-tuning simulation parameters such as variance of speeds, clustering speed factor, flocking radius and chaos threshold as well as chaos behavior will result in a more accurate simulation of a real evacuation scenario. To optimize parameter settings, a literature study or recorded data may be helpful. With continued work, both the Yerkes-Dodson's law and faster-is-slower may emerge. Insights from such simulations are highly valuable for emergency preparedness and efficiency of evacuations, ultimately saving lives.

VI. CONTRIBUTIONS

In the course of this project, each team member has played a significant role in its successful completion. The responsibilities were shared equally among the group members, ensuring that everyone contributed their fair share of time and effort towards both the simulation and report components of the project.

[1] Walden University. How Stress Impacts Decision Making; n.d. Last accessed 23 November 2023. Available from: `https://www.waldenu.edu/online-masters-programs/ms-in-clinical-mental-health-counseling/resource/how-stress-impacts-decision-making`.

[2] Joe R, Eric W, Yuen ACY, Shi M, Guan H. "Slower is Faster" by Considering of Give-way Evacuation Behavior. In: 2019 9th International Conference on Fire Science and Fire Protection Engineering (ICFSFPE); 2019. p. 1-6.

[3] Libretexts. 12.2: Yerkes-Dodson Law. Libretexts; 2022. Available from: `https://med.libretexts.org/Courses/Lumen_Learning/Book%3A_Wellness_(Lumen)/12%3A_Module_6B-_Stress_Management/12.02%3A_Yerkes-Dodson_Law`.

[4] Argun A, Callegari A, Volpe G. 8. In: Simulation of Complex Systems. 1st ed. Bristol: IOP Publishing; 2021. p. 8-1 8-14.

[5] Starcke K, Wiesen C, Trotzke P, Brand M. Effects of Acute Laboratory Stress on Executive Functions. Frontiers in Psychology. 2016;7. Available from: `https://www.frontiersin.org/articles/10.3389/fpsyg.2016.00461/full`.