Information Propagation Applied to Robot-Assisted Evacuation

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***Abstract*— Inspired by large fatality rates due to fires in crowded areas and the increasing presence of robots in dangerous emergency situations, we have implemented a model of information propagation among evacuees. Information about the locations of exits and the relative confidence of the individual in the location of the exit disseminated through a simulated crowd of people during an evacuation modeled after The Station Nightclub fire of 2003. True believers were added to this system as individuals who refused to accept exit information from others, instead preferring to head to their own exit. This system was then tested to find what percentage of true believers most likely existed in the actual fire. Using this true believer percentage, robots were added to the environment to guide evacuees to the nearest exit. The number of people who believed a robot's instructions was varied to find what percentage of people need to trust these robots in order to exploit information propagation and thus increase survivability. As a lower bound, we have found that 30% of the evacuees should believe a robot's instructions to significantly increase survival rates.**

I. Introduction

A fire in a crowded club is a frightening and confusing situation. Where is the nearest exit? Is the man shouting directions an employee or a patron with a bad memory? Who is believable? Over the years many such fires have happened in crowded clubs and bars. In The Station Nightclub fire of 2003, emergency personnel arrived within five minutes of onset of the fire, yet were helpless to prevent one hundred deaths [1].

Emergency evacuation robots offer many advantages over traditional methods of notification and guidance. Typically, the only real-time notification that people receive about the occurrence of an emergency situation is a buzzing alarm. The only guidance evacuees receive comes from stationary signs and their own recollection. Robots already present in the building can have an emergency guidance mode activate to provide an immediate, dynamic response. These robots can be specially designed for the task or they can have a normal function such as tour guide, mobile information kiosk, or security. The robots can approach people and guide them out of the building with no danger to emergency personnel [2], [3].

For these robots to be effective, they must be trustworthy. Rushed and possibly panicked evacuees will not follow directions from a source they do not trust. In The Station Nightclub fire, evacuees followed directions from nightclub employees, policemen, and firemen because they trusted those sources [1]. This paper explores the ratio of people who need to trust a robot guide to significantly improve evacuation rates.

Before considering robot guidance for these evacuation scenarios, we must first understand how people communicate necessary information among each other in an emergency. Information about viable exits must propagate in some way during an emergency, whether it be directly through verbal communication or indirectly through gestures and movement. In any reasonably sized group, there will be individuals who will be thoroughly convinced that their memory of the best exit is correct and thus will not be receptive to the opinions of surrounding evacuees. We began by determining what ratio of such true believers to uncertain individuals were present during The Station Nightclub fire. Then we added guidance robots to the scenario and varied the percentage of evacuees who believed a robot's instructions to find the minimum percentage necessary for significantly better survival rates.

II. Background Information

A. Panic Models

Various standards organizations have performed extensive studies after mass casualty evacuation events. One such study was performed by NIST after a fire in The Station Nightclub killed 100 people [1]. This study decided that two of the main reasons for the high casualty rate was the fast spread of the fire and a major stampede at the main exit. The fire department was able to respond within five minutes of ignition, which is nearly ideal, yet the fire was so bad that no firemen could enter the building until the entire fire was extinguished. As much assistance as possible was rendered at the exit points and windows, yet a majority of the people who were able to escape still had injuries requiring hospitalization and few who escaped more than one minute after the start of the evacuation survived. The study found that the emergency responders were blameless, however the night club made several mistakes and the local fire code was quite deficient. In addition to recommendations about fire suppression standards, NIST concluded that better training of night club employees regarding evacuation protocols and better notification of exits would have helped considerably. The NIST simulations were later corroborated and extended in [4].

Several studies have been performed on how people react in emergency situations. One study interviewed 128 survivors from a fire in the Solarium of the Summerland Leisure Complex in 1973 [5]. Sime found that individuals with strong ties to a group were less likely to panic and try to escape in a selfish way than previously thought. Families and groups of friends were more likely to make escape choices that were better for the group as a whole. Sometimes, particularly tight groups would exhibit this behavior at great personal risk. Another study analyzed video of crowds panicking during the 2006 Hajj in Mecca, Saudi Arabia [6]. The researchers plotted the position and velocity of each person in the area immediately in front of a bridge entrance. From this, they determined when the crowd transitioned from laminar to stop-and-go or turbulent flows.

A final study experimented with what exit individuals chose in a simulated emergency [7]. Benthorn recruited volunteers and had them test an emergency situation at an IKEA store. Each volunteer was given a headset which played an alarm and gave instructions to evacuate as quickly as possible. The study found that when volunteers could see closed exit doors nearby they still preferred to go out through the front of the store; however, when they could see an open exit door (with an outside view) then they were more likely to take it regardless of distance.

B. Aircraft Evacuation

Several experiments have been run to determine how people evacuate airplanes during emergencies. Muir has performed many tests with over one thousand paid volunteers to discover how people behave during an evacuation. During one test, the researchers tried several different aisle widths in front of the wing exits [8]. They determined that wider aisles (up to approximately 20 inches) allowed more people to evacuate. Greater than 20 inches of width and the aisle became wider than the exit itself, so evacuees assumed that more than one person could leave at a time. This was not possible due to the width of the exit itself, so a bottleneck formed in the exit row. Muir also examined what happened when volunteers were given extra incentive to evacuate quickly. This incentive was an additional $7.75 over their pay as volunteers if they could be among the first 50% to evacuate. For over-the-wing exits, incentives actually increased the mean time for evacuation. Some volunteers would push through bottlenecks to get out faster, which only delayed the group as a whole. Volunteers would also climb over seats (the authors note that not all seats were empty) to jump ahead in the line. This selfish and somewhat irrational behavior complements Sime's work in determining when groups work together to evacuate.

C. Exit Sign Design Constraints

Various standards agencies have undertaken several exit sign studies [9], [10] that can be used to inform how far a person can see in a smoky room. In [11] it was found that there is a small difference between the distance at which people with seeing disabilities can recognize an exit sign (mean of 13.9-14.6 meters depending on the sign) versus those without seeing disabilities (14.5-14.7 meters). The study also found that being close enough to read the word "Exit" was not necessary for recognizing the meaning of the sign.

III. Related Work

A. Evacuation Assistance Robots

In previous evacuation robot research, robots with directional audio beacons [12] were deployed in optimal positions to reach as many people as possible [13]. These robots were shown to decrease the total amount of time to evacuate in a simulation of an emergency. Physical robots were also deployed in a building to show that the system can automatically redeploy due to the loss of a robot. This research focused on using the robots primarily as static beacons to attract attention to the best exit.

An experiment has also been performed where a humanoid tour guide robot attempted to act emotional to engender human trust during a simulated emergency [14]. The robot started by guiding the human on a tour, then reacted with surprise to a blackout and finally directed the human to exit. The researchers found that the robot was more believable when it displayed an appropriate level of emotion for the situation.

Most research in emergency robotics has focused on assisting human personnel in search and rescue applications. Bethel and Murphy studied how volunteers reacted to rescue robots in a simulated urban disaster [15], [16]. They created several recommendations for how robots should approach, contact and interact with the victims. For the approach and other motions, the researchers suggest using smooth acceleration and deceleration. In contrast, typical robots are usually jerky when moving in an unknown environment. The researchers also suggested using blue lighting around the robot to convey a sense of calm. For interaction, they delineate different "zones" which the robot can occupy: the intimate zone (0 to 0.46 meters), the personal zone (0.46 to 1.22 meters), the social zone (1.22 to 3.66 meters) and the public zone (further than 3.66 meters). Robots are assumed to stay in the social zone or closer. To communicate, the researchers assumed that the robots would have to be in the intimate or personal zones. They suggested using voice communication to reassure the victim and music when there is no information to communicate.

B. Information Propagation and True Believers

Recently, work has been done on how committed minorities (or true believers) can affect a larger population of people [17]. The researchers found that just 10% of committed minorities can sway the entire population. A simulation of the Naming Game was run until all agents agreed. Their results indicate that consensus occurs much faster with committed minorities. They further hypothesize that their results may explain the committed minority phenomenon that sociologists have noted elsewhere in politics and culture. This work follows other investigations into social consensus and alignment [18], [19].

IV. Methodology

In order to find the critical percentage of evacuees who need to believe the robots, we first defined a model for human movement during an evacuation. Next, we defined a model for how information about exit locations propagates during the evacuation. True believers were created to act as people with unswayable beliefs in exit location. At this point, the model was tested to determine what ratio of true believers existed in The Station Nightclub Fire. Then, a robot policy was created specifically for the simulation environment of The Station Nightclub fire. Finally, the information propagation model was modified to allow robots to give exit beliefs to evacuees. Simulations indicate what ratio of evacuees need to believe robot directions to create a significant difference in survival rates, given that information can propagate via evacuees.

A. Human Behavior

According to [7], each person in an evacuation has an exit in mind at the start of an emergency. Most, if not all, people will use the front doors as a first choice. This was modeled by giving each person a belief that there was an exit (e_0) at a Gaussian random perturbation ($g(\mu, \sigma)$ below) from the main entrance (see Equation 1). If an individual happened to see an exit along the way, they transferred their exit location belief to that exit. Some individuals will be "true believers" who cannot be easily convinced that their exit is wrong. Other individuals will be suitably unsure of their chosen exit such that they are easily swayed by true believers and those who follow the true believers. This was modeled using a confidence parameter where true believers and those who can directly see exits had 100% confidence and others had 0% confidence initially (Equation 2).

$$e_0 = e_{main} + g(\mu = 0, \sigma = 4.2) \tag{1}$$

$$c_0 = \begin{cases} 1.0 & if\, true\, believer \\ 0.0 & otherwise \end{cases} \tag{2}$$

Each individual finds the unit vector ($\hat{v}$) from their current position (x_i) to their chosen exit (e_i) at each iteration of the simulation (Equation 3). The individual then attempts to move along that vector at his or her particular speed (s). If this movement causes collision with an obstacle or another person then the individual perturbs his end goal using Gaussian noise with a mean of 0 and a standard deviation of 1 distance unit (approximately $\frac{1}{12}$ of a meter) and a step along that path is again taken. If this perturbation still fails to place the individual in an open area then another perturbation is applied to the original goal. If ten tries fail to produce an open space then the individual is considered to be blocked in his or her original position for this iteration (Equation 4).

$$v = x_i - e_i \tag{3}$$

$$x_{i+1} = \begin{cases} x_i + s * \hat{v} & if\, clear \\ x_i + s * (\hat{v} + g(\mu = 0.0, \sigma = 0.08)) & if\, blocked \\ x_i & otherwise \end{cases} \tag{4}$$

B. Information Propagation

To model how knowledge of exits propagates through evacuees, we assume that individuals are capable of communicating the information they have about their exit as well as their confidence in their memory. In a real emergency it is unlikely that every person actually tells each other person where their exit is, however some information is exchanged simply by observing the trajectory of another person and any facial expressions he or she may be exhibiting.

Each person has a neighborhood that sets a range limit on how far information can be exchanged. Within this neighborhood, each person compares his or her exit with every other person's exit. The maximum confidence (c_y) is chosen as best, according to Equation 5. If this maximum confidence is less than the individual's confidence (c_i) then the individual will take the new exit (e) (Equation 6). Each time a person accepts a new exit location he or she also accepts the confidence degraded by a factor (a) (Equation 7).

$$c_y = max_{x \in N}(c_x) \tag{5}$$

$$e_{i+1} = \begin{cases} e_y & if\, c_i > c_y \\ e_i & otherwise \end{cases} \tag{6}$$

$$c_{i+1} = \begin{cases} a * c_y & if\, c_i > c_y \\ c_i & otherwise \end{cases} \tag{7}$$

C. Robot Behavior

The behavior of the robots was kept as simple as possible. Each robot was given two locations to oscillate between. Each location had a corresponding direction that the robots gave the humans. Directions were given with the goal of keeping people on course to the closest exit while also keeping congestion low at the exit itself. This was achieved by having the robot alternate between directing people to a holding area and directing people to a given exit. Holding areas were chosen manually before the simulation. For this environment, three holding areas were chosen: one in the center, one on the left side of the top wall and one on the right side of the top wall. These areas were found to be sufficiently spread out to keep the humans in three groups but sufficiently close to allow individuals to move from the holding areas to the exit quickly. A holding area was chosen for each exit; however, four robots were used because the main entrance is twice as large and thus could handle additional people guided by a second robot. The initial robot positions as well as the directional information pointing to the holding areas and exits are all shown in Figure 1. Each exit and robot is in red, the holding areas are in blue, and walls are in black. The robots were assumed to be simple platforms that could not detect humans as anything but obstacles and simply worked on timers to change places. Robot obstacle avoidance was implemented in the same way as the simulated human obstacle avoidance.

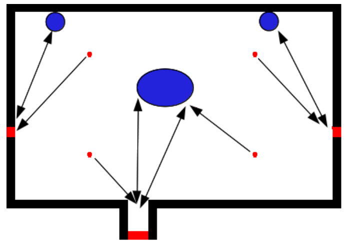

Fig. 1. Directional Information Given to Humans by Robots

D. Human-Robot Information Propagation

There is not yet any evidence to show how confident humans are in commands given by an autonomous robot during an emergency evacuation. It is assumed that some humans will believe the robots, but others will ignore or even consciously disobey. We have modified the human exit information propagation model to determine how many evacuees must believe robots to produce a significant change in survival rate. Some humans are assumed to believe robots whereas other humans will ignore the robots. The humans who do believe the robots ($c_r = 1.0$) are modeled such that they become true believers in whatever direction the nearest robot is advising. Their exit (e_{i+1}) is set to whatever direction the robot is giving (e_r, Equation 8). Their confidence (c_{i+1}) is set to maximum and they propagate information to other humans as before (Equation 9). In the case where an individual is a true believer and a robot believer, the robot's directions take precedence.

$$e_{i+1} = \begin{cases} e_r & if\ c_r = 1.0 \\ e_i & otherwise \end{cases} \tag{8}$$

$$c_{i+1} = \begin{cases} 1.0 & if\ c_r = 1.0 \\ c_i & otherwise \end{cases} \tag{9}$$

V. Human to Human Belief Propagation

Before an experiment can be run using robots, we must first determine a valid ratio for true believers for The Station Nightclub fire. A simulation of the nightclub was created, complete with the 440 people in attendance that night.

A. Experimental Setup

All experiments took place in a simulation of The Station Nightclub fire (the simulation environment can be seen in Figure 1, real nightclub design in Figure 2). The nightclub is simulated as the combined area of the three large rooms: the main room, the sun-room and the bar. No interior furniture or stages have been simulated. The hallway that caused many of the casualties is simulated as coming out of the front of the nightclub instead of contained within for technical reasons related to collision management in the simulator. The main room is 16.6 meters by 10.9 meters and connected to the sun-room by 10.9 meters of open space [1]. The sun-room is 10.9 meters by 4.6 meters. The bar is 7.6 meters by 8.5 meters and is connected with the other rooms by a large passage. The main exit is between the sun-room and the bar. Two other exits were simulated, one from the bar and one from the west side of the main room.

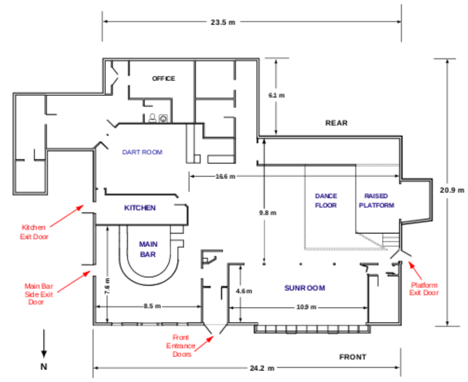

Fig. 2. Actual Station Nightclub Floorplan

Simulations were initialized with 440 people inside the club. Each person was given the ability to see exits, robots and humans at a range of 3.5 meters. This distance was chosen by scaling the distance an exit sign can be seen [11] to account for the reduced distance at which an unlit person, robot, or exit door can be seen in a crowd. Each person's neighborhood was defined as all other individuals in sight. The confidence degradation constant was set to 0.9. Initial true believers were varied from 0% to 100% of the population at increments of 10%. Positions at the start of each experiment were randomized. The random seeds were kept such that each experimental setup could be run at each variable level. Thirty trials were run for each independent variable combination. The average human walking speed is approximately 1.4 m/s, so each human was given a speed within a Gaussian random position about that mean. It is estimated that all survivors evacuated the nightclub within 1 minute of the fire alarm, so experiments were run until one minute of simulated time passed. Each iteration of the simulation was $\frac{1}{16}$ of a second in simulated time. The measured results of each test was the number of people who successfully evacuated within 1 minute.

B. Results

The results of the human to human belief propagation tests can be seen in Figure 3. As the percentage of true believers goes up, the number who can evacuate goes down. In other words, when more people listen to the others in their area, the survival rate goes up.

In the actual Station Nightclub fire approximately 220 people were able to escape through the doors. Only door evacuation was simulated here, so a t-test was performed (Table I) to see which percentage of true believers were statistically insignificant when compared with the actual number of survivors. This tells us that the total number of true believers in the nightclub was likely between 30% and 70%. This is a large range; however, the data taken from the actual event has a large error margin which prevents limiting the range.

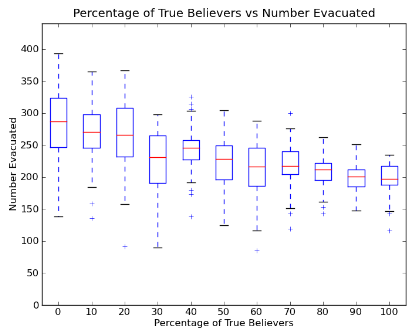

Fig. 3. Results of Human to Human Tests

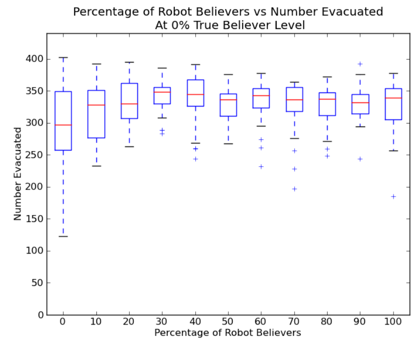

Fig. 4. Results of Robot to Human Tests at 0% True Believer Level

TABLE I

T-TEST RESULTS COMPARING HUMAN TO HUMAN TESTS AND ACTUAL SURVIVAL

Percent True Believers	P-Value
0	<0.001
10	<0.001
20	<0.001
30	0.418
40	0.009
50	0.506
60	0.245
70	0.767
80	0.013
90	<0.001
100	<0.001

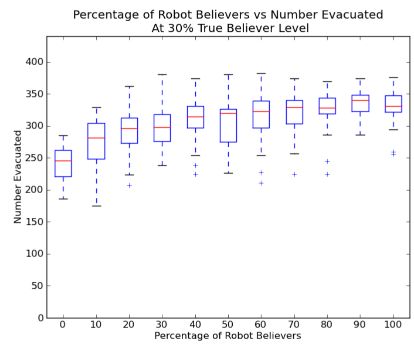

Fig. 5. Results of Robot to Human Tests at 30% True Believer Level

VI. ROBOT TO HUMAN BELIEF PROPAGATION

Evacuation robots were added to the simulations with true believer rates statistically insignificant when compared to the actual fire (30%, 40%, 50%, 60%, 70%) to determine what effect the robots had on survival rates. Tests were also run at 0% and 100% of true believers to determine the effects of robots on extreme populations.

A. *Experimental Setup*

For these simulations, humans were randomly chosen to either believe the robots or not. The percentage of humans who believed the robots was varied between 0% and 100% at 10% increments for each chosen true believer level. In the case that a human was both a true believer and a robot believer, the robot's directions took precedence.

Each robot was given a set of waypoints to move along to inform as many people as possible. Each robot was also given directional information to give to each human in range. The directional information for each robot is shown in Figure 1. Two robots were assigned to guide people towards the front entrance and one was assigned to each side entrance. For this simple robot model, the directions given are static and time based. The information was selected such that the evacuation of this particular nightclub would be optimized. It is assumed that any system that implements this work in the real world would take the time to customize directions based on their particular evacuation plan.

B. *Results*

With no true believers, any number of humans believing the robots significantly increased the survival rate (Figure 4). Table II shows the P-Values as compared to the without robot trial. Every trial with any humans believing robots was significant at the 0.05 level. Robot believer ratios between 20% and 90% were significant at the 0.001 level.

The results of the 30% true believer test can be seen in Figure 5. Here the robots had a significant impact on survival rate at the 0.001 level for all robot believer rates 10%-90%.

The results of the 40% true believer test can be seen in Figure 6. The results become significant when 30% of the people believe the robots. Results at 40% are very similar to those at 50-70%, so those graphs have been eliminated for brevity.

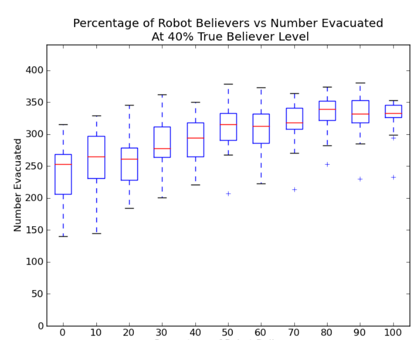

Fig. 6. Results of Robot to Human Tests at 40% True Believer Level

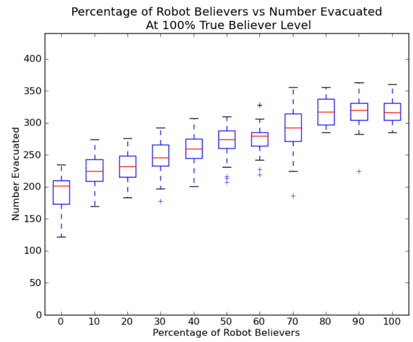

Fig. 7. Results of Robot to Human Tests at 100% True Believer Level

At the 100% true believer level (Figure 7), results are significant starting at 10% robot belief ratio.

Table II shows the p-values from the t-tests between each of the tests at each value with the corresponding non-robot test.

VII. Discussion

As a lower bound, just 30% of the humans have to believe the robot to increase survivability at a statistically significant level. As more people believe, we see a dramatic rise in survivability. When all humans believe the robots, over 100 extra people can make it out within the time limit. If we extrapolate to include window evacuations during the actual event then it is possible that all people would have made it out of The Station Nightclub in the 2003 fire. In general, standard deviation also dropped when robots were introduced, so more people consistently made it out.

In extreme cases where either no humans are true believers or where all humans are true believers, robots have a significant impact on evacuation rates at the level of 10% robot believers. Further testing is required, but it may be that evacuation robots will be most helpful in areas where most people believe they know the best exit, such as an office building. The people would almost all head to the front entrance, but the robots could guide some to side exits. Likewise, in areas where no one knows where any of the exits are, such as large malls, the robots can provide much needed guidance.

Adding robots to an evacuation introduces the risk that the robots themselves act as obstacles. For all percentages of true believers, holding robot belief at 0% produced no significant results when compared to tests when robots are not present. From this, we can conclude that the robots' presence had no effect on the simulation unless the people believed in the robots, thus the robots did not produce a noticeable impediment in the evacuation.

VIII. Conclusion and Future Work

We have implemented a model of information propagation among evacuees during an emergency that accounts for true believers. We tested this model on a simplified simulation of The Station Nightclub fire to find valid values of true believers. We then introduced evacuation robots and found that as long as 30% of the people trust a robot's directions there will be significantly more survivors.

The next item of future work is to find out how many people will trust a robot in an emergency. To this end, we have produced a three dimensional simulator to place people in an emergency situation and see how the human reacts when a robot provides directions. We will attempt to find the percentage of people who will believe a robotic evacuation guide and then try to increase this percentage by modifying the appearance and behavior of the robot. For most true believer values, diminishing returns were not seen until approximately the 80% robot belief level, so it would be advisable to create an evacuation robot that appeals to as many people as possible.

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TABLE II

P-VALUES OF ROBOT TO HUMAN BELIEF PROPAGATION TESTS COMPARED WITH NON-ROBOT TESTS

Robot Belief %	True Believer %						
	0	30	40	50	60	70	100
0	0.291	0.114	0.953	0.662	0.352	0.682	0.458
10	0.007	<0.001	0.107	0.010	0.004	0.360	<0.001
20	<0.001	<0.001	0.118	<0.001	0.001	<0.001	<0.001
30	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
40	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
50	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
60	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
70	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
80	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
90	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
100	0.005	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

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