Collective Dynamics

A Rumor has Spread like Wildfire? - Empirical Investigation of Information Propagation in Waiting Crowds

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Abstract Information propagation in crowds tends to have a negative image. A common narrative is that information about a danger spreads like wildfire and leads to panic. In contrast, using person-to-person information sharing in crowd management as a complement to other communication channels has been discussed less. Even though previous research indicated that information does not propagate easily in crowds, more detailed research is lacking. In this study, two different experiments are presented to provide initial insights. In the main experiment, five groups of 33-41 participants took part in a total of 35 runs. In each run, a person in a waiting group was given a message or command that had to be passed on, whereby the knowledge about the task, the relevance of the message and the input side were varied. In the second experiment, this procedure was repeated with two larger groups of participants ($n = 91$ and $n = 101$). Overall, results showed that information propagated better when people were properly briefed on their task and have performed it several times. There was also a tendency for a higher density to foster faster propagation and for participants to rely on the spoken word rather than seeing a behavior performed. Yet, some participants did not receive the information at all or did not pass it on. In general, the direction of communication (e.g., back to front or left to right) was not always the same but information was usually passed along in a similar direction from where it came.

Keywords Information propagation · crowd dynamics · crowd management · communication

1 Introduction

Communication is an essential part of human interaction. We talk with friends, family or at work, in pairs or in small groups. Generally speaking, people can be multipliers of information. If a person knows something, he or she might pass it on to others. However, this is not always the case; sometimes information is withheld - consciously or unconsciously, intentionally or unintentionally. The impact of people withholding information - often referred to as "stiflers" - and the proportion of people who receive a piece of information under different circumstances have motivated numerous theoretical works in recent decades [1–7]. Sudbury [8] was one of the first to use a simplified mathematical model to address this issue. He supposed that there are three types of villages: (1) those that have not heard of the rumor, (2) those that have heard of it and want to spread it, and (3) those that have heard of it but do not want to spread it further on. The villages then randomly call each other. If a village that does not know the rumor yet is called by one that wants to share it, the rumor is passed on. If a village that wants to share the rumor calls a village that already knows it, the first village loses interest and no longer wants to share it. All other calls have no effect. Given these assumptions, the probability of never hearing the rumor approaches 0.203 if the number of villages approaches infinity. Depending on the model and the parameters chosen, the exact number varies. However, most calculations indicate that information subside even if not all possible recipients have heard about it, and while the models are quite artificial and rarely have an empirical basis, this is definitely realistic. For larger crowds, such as concerts or religious gatherings, this fact could be especially relevant since these crowds typically consists of many smaller social groups and dyads which do not know each other. Even if people in waiting situations sometimes make contact with each other, they are usually more hesitant to talk to strangers than to people they know. Thus, the information transfer may be additionally impeded. Nonetheless, even when information is passed on, it does not always reach its recipient correctly. Simple models of communication, such as the Shannon-Weaver model [9], indicate that the transmission of a message between sender and receiver can be affected by various sources of interference (e.g., noise), and also the children's game "whisper down the lane" taught us about this from an early age.

1.1 Information Transfer in Crowds

Looking at research on large-scale events, spreading of a rumor is referred to as one cause of crowd accidents [10,11]. This assumption is often based on media reports of single disasters, in which, for example, is written "According to police officials present at the place of occurrence, a rumour about electric supply line falling on the crowd near the western exit gate of Gandhi Maidan spread like wildfire, triggering panic among people who ran for cover." [12] or "Witnesses said panic spread over rumours of suicide bombers." [13]. Empirical research revealed that ideas of false rumors spreading quickly in an emergency [14], or of information about something bad happening triggering crowd accidents [15] prevail among the general public as well. Drury et al. [14] showed that these assumptions are even held by professionals working in the field of public safety and emergency response. Aside from the fact that researchers criticize the emergence of panic [15] and assume that disasters are caused by multiple causes [10, 16], the notion that information spreads through a crowd like wildfire should be critically questioned, too. Not only do the general limitations of information transfer mentioned in the previous section contradict this view, but analyses of actual crowd accidents indicate that information travels poorly in very dense crowds, as people often do not realize how dangerous it has already become elsewhere [17, 18].

On the other hand, however, if there was a way for human-to-human information transfer to actually work well, crowd managers could make use of it. So far, there has been a variety of research on how to address people effectively in emergencies. For example, it is already established that personal approach (e.g., announcement, staff guidance) works better than the mere use of an evacuation alarm [19–21]. Additionally, Templeton et al. [22] recently published preliminary findings on the tone of voice when instructing people in face-to-face scenarios. Emergency personnel surveyed indicated that they find a facilitative tone, which conveys the requests as if the public is helping, and a teamwork tone, which creates a collective atmosphere, to be most effective. However, besides directly addressing people, the transfer of information between visitors could also be used. In fact, researchers have been arguing for some time that crowds should also be seen as a resource in emergencies that can be actively engaged [23–26]. But for this strategy, it is necessary to know whether information propagates in certain, predictable patterns, how reliable and quick information is passed on, and in which way a message has to be designed to ensure reliable and fast propagation.

Besides the propagation of mere verbal messages, it should also be considered that information can be accompanied by or trigger the execution of a behavior. In these cases, it is possible that information is not or not only distributed verbally in a crowd, but that an action propagates visually. For instance, a message might instruct people to move in a certain direction. While the message is likely to be passed on verbally at the beginning, at some point, people might just join the moving group without having received the word actively. From a psychological point of view, such behavior makes sense, since the well-known heuristic ”Imitate-the-majority” states that it is generally a reasonable idea to follow the actions of others [27, 28]. Nevertheless, of course, this does not mean that everyone blindly follows the majority. In line with this, Haghani et al. [29] concluded in a comprehensive review that the idea of so-called herd behavior in an evacuation context is empirically untenable. Instead, the behavior of individuals partly depends on the behavior of others, but there are many factors determining the extent, for example, the type of behavior (e.g., movement initiation, exit choice) or the degree of uncertainty or urgency of the situation. People may even behave exactly contrary to the majority and/or follow a minority.

Similarly, studies on behavior in non-emergency situations showed that although people influence each other, they never all behave the same way. For instance, when a group of people on a street gazed upward at a certain point, some of the passersby followed this gaze [30]. The proportion of passersby looking up increased as the size of the stimulus group increased, up to 40% at a group size of 15. How long they looked up additionally depended on their own speed as well as on the density of the crowd around them. Lügering et al. [31] found out that the likelihood of someone starting to push increased by up to 30% if a person had a large number of contacts with other people pushing. All in all, however, these effects are rather small. Furthermore, it is important to keep in mind that behavior in a crowd is often only visible to a limited number of people. Those who stand too far away or with their backs to it may not even notice it and as Wirth et al. [32] recently showed, people are only influenced by the motions of neighbors who are visible to them. In other words, people who are in close proximity but occluded by others do not affect people's behavior. In extremely dense groups, this aspect is particularly relevant, since perception is usually limited to the people in the immediate vicinity [18]. However, when it comes to behavior that is visible to almost everyone, this can be highly appealing – sometimes with serious consequences. In their analysis of the witness statements of the Love parade disaster 2010, Sieben and Seyfried [18] showed that as soon as the first visitors began to climb the stairs or the poles out of the dangerously dense crowd, others tried to reach these places as well. While some moved there deliberately because they saw an opportunity to escape, others were carried along by the movement of the crowd which overall resulted in a densification in these areas.

Looking at these findings, it becomes clear that there is actually little research on how messages and behaviors propagate in crowds. Nevertheless, assumptions on person-to-person communication and sharing of information have already been incorporated into some crowd models. For example, Henein and White [33] implemented an egress scenario, where agents have different knowledge about the world and the exits. This knowledge can be expanded through discovery of spatial information or communication with others. Communication occurs when an agent wants to move to a field that is already blocked by another agent. The moving agent then communicates its worldview to the blocking agent in order to align it with the former agent's goals. Other models simply suppose that agents receive the information about hazards or exits when they are close to agents who are already informed [34, 35]. Such assumptions usually lead to the information propagating rather quickly. Kullu et al. [36] distinguished between meaningful and hollow communication and defined various complex conditions for different scenarios in which two people talk to each other with a certain probability (e.g., when someone just wants to communicate and a target is nearby or when someone wants to ask for directions during an evacuation). Furthermore, Yehua and Jing [37] addressed an idea similar to the newspaper articles cited above, namely that information transmission between people within a certain distance around a hazard leads to panic behavior unless there is beneficial calming information (e.g., proper instructions). Hoogendoorn et al. [38] additionally integrated the interplay of information and emotions into their model and their simulation showed that information propagates more or less easily depending on its relevance, its positivity and the level of fear of the agents.

1.2 The Present Study

This paper presents two experiments to address the research gap on information transfer in crowds and to provide initial empirical evidence. In order to simplify spatial information, we studied information propagation in a static phase of a moving crowd (in contrast to the models just introduced). In the first experiment, small groups (n = 33-41) took part in several runs, both as repeated runs (i.e., each group performed seven runs) and as between-subject runs (i.e., five different groups took part in the experiment). In the second experiment, we had two larger groups (n = 91 and n = 101), each performing one run. In every run, information was given to a person in the waiting group who then had to pass it on. For the analysis, the propagation of the information was first depicted descriptively and checked for any noticeable features. Then, it was examined whether there was a system in the direction the information traveled in. Finally, the speed of the information was investigated descriptively. This first part of the analysis was exploratory. In addition, one hypothesis was tested: We hypothesized that the information would travel faster if the group was more practiced, the people stood closer together and the information was additionally linked to a behavior, as it could then also be passed on visually. In terms of density, our hypothesis was contrary to the literature, which suggests that information is transmitted worse in extremely dense crowds. However, we assumed that at the low to moderate densities that we created in our experiment, it would be advantageous for the participants to be closer together since communication paths would be shorter and information could be overheard.

2 Method

2.1 General Experimental Set-up and Procedure

The analysis presented in this paper is based on two different data sets. The first one - which is our main data set - was collected during a series of experiments in the foyer of a building of the University of Wuppertal in 2022. The second one was collected during a series of experiments in an event hall in Duesseldorf in 2021 (see [39] for a detailed description of the overall organization of these experiments). The Duesseldorf experiment was designed to test the method and to initially examine the systematics in the propagation of information. In addition, these runs could be used for further interpretation and generalization of our results.

The general procedure was the same for both experiments and, in both cases, a bottleneck set-up was used (Figure 1). At the beginning of each run, the group of participants gathered within the experimental area and, on a signal, started to move through the bottleneck. About five seconds after the start, the flow was interrupted and one of the experimenters gave a piece of information to a participant standing at the edge. The information should then be passed on to the other participants. After an interruption time of maximum two minutes, the group was signaled to move again, passed the bottleneck and reassembled in the experimental area. In both runs of the experiment in Duesseldorf, the

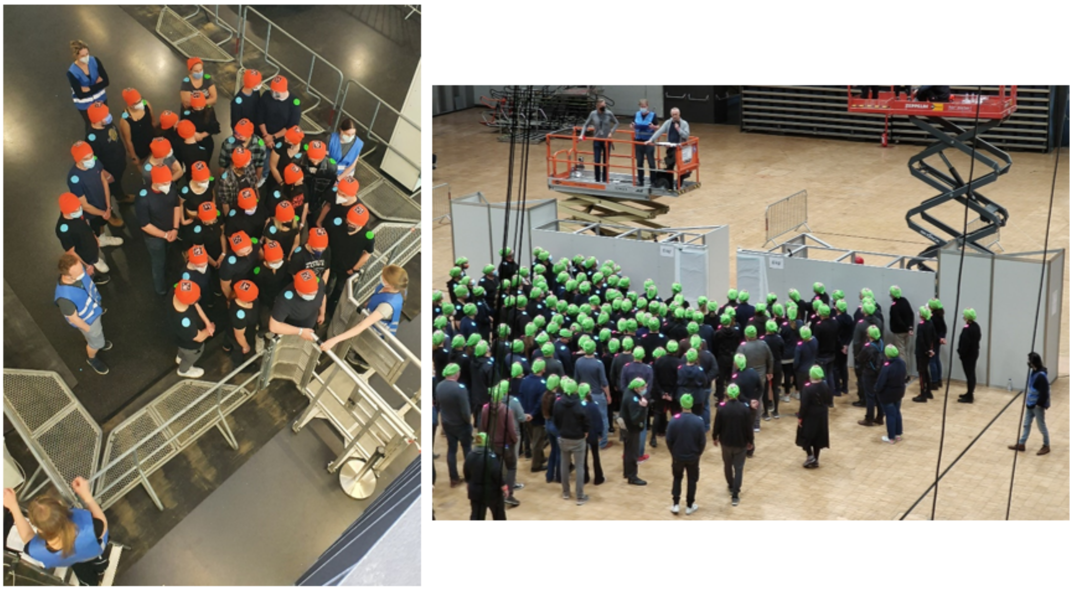

Figure 1 Experimental set-up of the Wuppertal (left) and the Duesseldorf (right) experiment.

input information was "This is an additional experiment; we are playing "whisper down the lane". Tap yourself briefly on the shoulder as a sign that you received the information, and then pass it on." Both times, it started from the right side of the crowd. As the experimental design of the Wuppertal experiment was more complex, it is described in more detail below. Table 1 provides an overview of the experimental set-ups and procedures to compare the two experiments. In both experiments, the runs were filmed through an overhead camera and the participants wore colored hats, which allowed to analyze the resulting videos with the software Petrack (e.g., to extract the trajectories) [40]. Further, in accordance with the Covid-19 rules back then, a face mask had to be worn during both experiments.

	Wuppertal	Duesseldorf
Set-up	Bottleneck	Bottleneck
Number of groups	5	2
Number of participants per group	33-41	91-101
Number of runs per group (relevant for this study)	7	1
Type of runs	Surprise, message, command	Command
Side of information input	Left, right, back, front	Right
Length of interruption	35-120 sec	120 sec

Table 1 Overview of the experimental set-up and procedure in the Wuppertal and Duesseldorf experiments

2.2 Procedure of the Main Experiments

The Wuppertal experiment took place on two mornings of a three-day series of experiments in May 2022. In total, it was repeated five times with different groups of participants, each consisting of 33 to 41 people. However, since a few participants already left the experimental area in the first seconds until the stop signal, the actual number analyzed per run varied between 30 and 38.

Upon arrival, the participants read the conditions of participation and signed the informed consent. They were then given an orange hat with a personal ID code, a wristband with the corresponding number, and a green and a blue sticky dot. The green sticky dot was to be placed on the left shoulder and the blue one on the right shoulder. Furthermore, age, gender and body height were noted using the personal ID. The height was required for the processing of the videos in Petrack. After the preparations were completed for all participants, the group gathered in the experimental area and was greeted by the main experimenter. The group was told that their task would be to walk at a brisk pace, without pushing, through the bottleneck and gather back in the experimental area afterwards. The participants were also informed that there would be a questionnaire (paper-pencil) after some of the runs and that crowd noises would be played throughout the experiment to make it less quiet. After answering all questions, the group positioned itself in front of the bottleneck and the experiment began.

The experiment consisted of a test run without interruption, seven runs with interruption and information input (with the first one being a surprise run, see 2.2.1), and three to four further runs, which, however, were conducted with a different purpose and hence will not be addressed in this paper. In total, everything took about 1.5 hours. During this time, the main experimenter stood slightly elevated at the head end outside the bottleneck and four additional experimenters stood at the four sides of the group to input the information without attracting much attention. The experimenter standing in front additionally blocked the bottleneck with her arm whenever participants were not supposed to pass through it. All experimenters wore blue vests to make them recognizable as such. Each run began with a ”Go” signal and the opening of the bottleneck. After finishing all runs, the participants were thanked, they returned their hats and codes and received 15 € for their participation.

2.2.1 Runs 1-2: Test Run and Surprise Run

The experiment was advertised as a social interaction experiment. Thus, at the beginning, the participants did not know the actual purpose. In order to maintain this cover story, each group started with a test run in which the participants simply walked through the bottleneck (without interruption). This also served to familiarize them with the procedure. In the second run (i.e., the surprise run), the flow was then interrupted about five seconds after the start for no apparent reason. This was followed by a 60-second waiting period with no interaction with the participants. Shortly before the end of this period, the

Run	Type	Information	Position of Input
3	Command	“Peel the green sticky dot off your shoulder.”	right
4	Message	“The color is yellow.”	back
5	Message	“The color is red.”	left
6	Command	“Peel the blue sticky dot off your shoulder.”	front
7	Message	“The color is purple.”	front
8	Command	“Tap yourself briefly on your own shoulder.”	back

Table 2 Exemplary sequence of runs 3-8

experimenter, who was standing slightly elevated, made a secret sign to the experimenter standing to the left of the group (i.e., touching one elbow with the hand of the other arm). This experimenter then discretely approached one of the participants standing at the edge and whispered a message to her/him, which s/he was supposed to pass on. Depending on the condition, this message was either ”We have a technical problem.” (relevant condition) or ”The color is blue.” (irrelevant condition). Three of the five groups received the relevant information and the other two the irrelevant information. After another 60 seconds, the bottleneck was reopened, participants passed through it and assistants instructed them to fill in a questionnaire. After everyone had gathered in the experimental area again, the true purpose of the study and the interruption was revealed. The participants were now informed that further interrupted runs would follow, in which they were to pass on either a message or a command which they were also to execute (according to “whisper down the lane”).

2.2.2 Runs 3-8: Interruption Runs

The surprise run was followed by six interruption runs. In order to keep participants' attention directed to the front, a colorful 2D animation video (without sound) was played on a screen. At the beginning of each interruption, either a message or a command was given by one of the four experimenters. Each group received three different messages and three different commands. The type of information and the side of the input was randomized (two times each from the front and from the back, and one time each from the right and from the left side). However, both the order of the messages and the order of the commands as such were the same for each group. For an exemplary sequence, see Table 2. The interruption phase lasted between 35 and 60 seconds ($M = 48$, $SD = 11$) and the participants filled in a short questionnaire after each run.

2.2.3 Questionnaire

The questionnaires were mainly intended to record whether the information was received and passed on. However, they differed somewhat depending on the type of the run. The questionnaire after the runs for passing on a message was the shortest. It only asked whether the participants received the message (yes/no) and, if so, what the message was (free text), how often it was heard (1-2x, 3-4x, more than 4x), and whether it was passed on (yes/no). In the runs where a command was passed on, the questions were a bit more extensive. Likewise, the participants stated if the command was received and, if so, what it was, and whether it was passed on. Furthermore, it was asked whether the command was heard, seen, or both, whether the behavior was executed (yes/no), and what triggered the execution (hearing or seeing it). If the command was (also) heard, it was asked how often (1-2x, 3-4x, more than 4x). If the behavior was (also) seen, participants indicated in how many people they observed the behavior (1-2 persons, 3-4 persons, more than 4 persons), and – in case the execution was triggered by seeing the behavior – whether they imitated the behavior immediately after observing it once or only when they observed it several times. For the surprise runs, the questionnaire was the same as for the message runs but there were additional items on participants' feelings during the run and on other psychological constructs. However, these items were not included here as it would be beyond the scope of this paper. In order to later link the answers to the questionnaires with the people in the videos, participants wrote down their personal ID on each sheet.

2.3 Participants

Both experiments were advertised through various channels, including print and social media, email lists of previous experiments, lectures and other information channels of multiple German universities. In the two runs of the Duesseldorf experiment, we had $n = 91$ and $n = 101$ participants with all but one person participating in only one of the two runs. Of the 191 participants, 46.6% were female, 50.8% were male, and 2.6% did not specify their gender. The 189 participants who reported their age were on average 41.3 years old ($SD = 17.1$). The overall sample ($N = 184$) in the Wuppertal experiment was similarly balanced in terms of gender (51.6% female, 46.7% male, 1.6% non-binary), but considerably younger ($M = 24.5$, $SD = 8.4$). This can be explained by the fact that the experiments in Duesseldorf explicitly aimed at a broad sample, which was fostered by the temporal framework (i.e., participants took part in different experiments during a complete day), the location (i.e., an event hall in the city), and a broad recruiting. In contrast, the experiment in Wuppertal lasted only 1.5 hours for each participant, took place in the foyer of a university building, and was advertised mainly through university channels, leading to a primarily student sample.

2.4 Data Preparation and Statistical Analysis

In order to analyze the videos in addition to the questionnaire data, they were processed as follows: First, the path on which the information traveled through the group was traced by looking closely at the videos, i.e., it was manually identified who communicated with whom. To do this, a screenshot was taken from the video about one second before the information input and from where to where the information was shared was marked with arrows as precisely as possible. The focus here was on verbal transmission, meaning that, in the command runs, cases in which participants performed the behavior without being

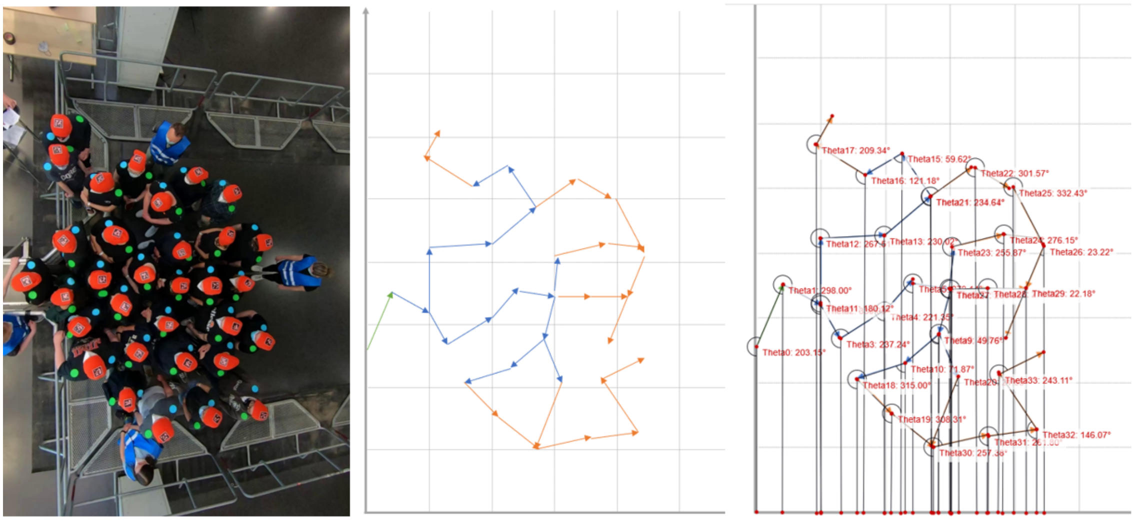

Figure 2 Identification of the direction of information transmission. (a) A screenshot of an exemplary run around one second before the information input. (b) Communication paths indicated by arrows (green = information input, blue = first 15 communication paths indicating the initial propagation, orange = all further communication paths). (c) Determination of the angles using WebPlotDigitizer. The coordinate system is for visual orientation only and has no further meaning.

actively talked to were not included. Then, the orientation of the arrows measured in angular degrees was determined using the WebPlotDigitizer [41]. Based on the orientation of the videos, an input from the right side corresponded to an angle of 0°, from the back to 90°, from the left side to 180° and from the front to 270° (Figure 2).

Additional to the directions, we identified the time at which participants received the information and, if applicable, executed the behavior. For this, the software Petrack was used which extracts the trajectories of all participants in the experimental area during an experimental run. This resulted in a data set including the exact position of every participant at each time point. Via an annotation function it was possible to enrich this spatiotemporal information with the data on the information propagation. Similarly to the analysis of the direction of information, this was done manually by carefully watching the videos. In addition, it was noted whether participants received and executed the message/command correctly. This was based on the responses from the questionnaires, particularly for the message runs. Please note that we always marked the first moment in which the participants received the information. If a person was contacted more than once, this was no longer taken into consideration. In the command runs, the participants typically were assigned a time for both the receipt of the message and the execution of the behavior. However, if the command was executed without prior communication, only this time was marked (even if there was an act of communication afterwards). If participants indicated in the questionnaire that they knew about the information but no one communicated directly with them and they did not perform the behavior, the moment was identified in which it was most likely that they became aware of it (either by overhearing

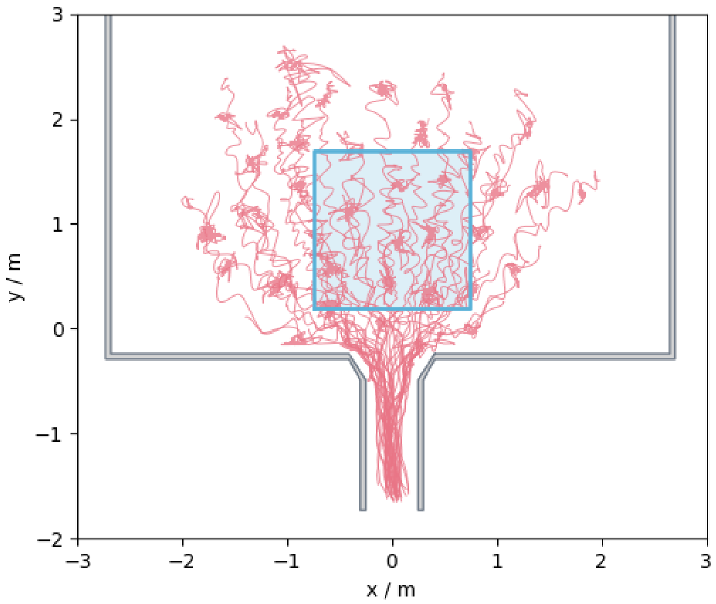

Figure 3 Measurement area for density calculation. The picture shows the experimental area (in meters) with individual trajectories (in red) of one exemplary run. "Knots" indicate the places where participants stood still. The blue square indicates the measurement area for the density calculation.

or by seeing the command being performed). These two preparatory steps (i.e., identifying communication paths and time points of receipt) were done by a person who was not aware of the research questions and the hypothesis. To ensure data quality, several runs were additionally checked by a second person revealing no systematic error and a satisfactory overlap. Finally, the average density in the measurement area (Figure 3) over the 25 seconds after the information input was calculated for each run using Pedpy [42].

Since this is an exploratory study, we used mainly descriptive statistics derived from the questionnaire data and videos to answer the research questions. In order to identify possible systematics in the direction of propagation, the angles of the communication paths were relativized to the angle of the intended information input of the respective run (right = 0°, back = 90°, left = 180°, front = 270°). Of course, the actual input did not always occur at this ideal angle, but was slightly different depending on the spatial positioning of the experimenter and the addressed participant. However, we assumed that the participants mainly noticed the information coming, for example, from behind and that the exact relation in space was not important. Lastly, we determined the time at which a certain number of participants received the respective information as well as the speed of propagation and calculated a linear multiple regression with the type of information (message vs. command), the sequence of the runs (i.e., first, second, third,...), and the respective density as predictors. The propagation speed in each run was defined as ratio of the total number of participants who were informed and the time span between the input of the information and the last person receiving it. Thus, the value indicates how long it took on average to inform one person, i.e., a higher value means a slower speed, and is therefore referred to as “transmission time”.

For the analysis of the Wuppertal experiment, two message runs had to be excluded: In one run, the first participant walked around the group and informed several others; in the other run, one or two participants apparently spoke very loudly while sharing the message since suddenly several others who were actually standing farther away seemed to be informed. These behaviors were indeed nice and fostered a quick information propagation. However, they were not in accordance with the experiment instruction and therefore made the runs less comparable. Consequently, in addition to the five surprise runs, 28 interruption runs (13 message runs and 15 command runs) were taken into account.

3 Results

3.1 Wuppertal

Overall, the answers given in the questionnaires corresponded almost always to the observations in the videos (e.g., who received or executed a command). Nevertheless, there were minor discrepancies, such as a person who claimed not to have known about the message, but who was clearly spoken to. Also, there were some questionnaire responses that did not match (e.g., someone stated not having received the message, but then heard it 1-2x) or responses were missing. Since it was not possible to differentiate which information was correct, we kept all data as it was. This resulted in small deviations in the frequency data within the questionnaires as well as between the questionnaires and the observations in the videos, with minor discrepancies tolerated, while major discrepancies were addressed at the respective point.

3.1.1 Descriptive Statistics

Surprise Run. Due to the small number of the surprise runs ($n = 5$), only a descriptive analysis was reasonable. Table 3 shows how many people received the information per run (according to video observation) and how many seconds after the input the transmission of the information stopped (= duration of transmission). Please note that in one run of the relevant condition, one participant stated to know about the information, but it was not clear from the video how that person could have known. In another relevant run, however, one participant was clearly spoken to, but claimed not to have known. The mean values between questionnaire and video data across the relevant condition were therefore the same, even if there was a small discrepancy between single runs. Results showed that, on average, the information propagated similarly in the relevant and the irrelevant condition with a similar amount of people informed and a similar duration of transmission.

		Number (percentage) of informed participants	Duration of information transmission (in sec)
Relevant Condition ("We have a technical problem.")	Group 1	8 (24.2)	9
	Group 3	10 (27.0)	16
	Group 5	10 (31.3)	19
	Mean	9.3 (27.5)	14.7
Irrelevant Condition ("The color is blue.")	Group 2	14 (46.7)	18
	Group 4	6 (15.8)	20
	Mean	10 (29.4)	19

Table 3 Descriptive data on information propagation in the surprise runs

Runs 3-8. According to the questionnaire data, 95.1% of the participants received the message across all message runs. Of those, 43.0% heard it one or two times, 30.6% heard it three or four times, and 26.5% heard it more than four times. A large percentage of participants also reported passing the message on (86.7%). Likewise, in the command runs, a high proportion (85.0%) received the command. Of those, about two-thirds both saw and heard the command (65.7%), 24.8% only heard it and 9.5% only saw it. When the command was heard, it was received one or two times in 44.7% of the cases, three or four times in 37.9% of the cases and more than four times in 17.5% of the cases. For observing the execution of the command, an inverse pattern emerged: A minority observed the behavior with only one or two persons (20.5%), 31.5% reported seeing it with three or four persons, and nearly half (47.9%) saw it with more than four persons. Although the absolute number of people who answered this question was about 35% higher than the number who indicated to have seen the behavior at all, the pattern was the same when only taking this subgroup into account. The majority of those who received the command also executed it (90.3%), and many passed it on (70.8%). When asked what triggered the performance, 82.3% stated performing the behavior because they heard it and only 17.7% because they saw it. When asked whether the command was executed after one or more observations (if it was executed after seeing), more than half of the responses were from participants who actually stated that they executed the command after hearing. When analyzing solely the data of participants who claimed executing the behavior upon observation, 71.4% performed it only after seeing it several times (instead of once).

According to video observations, in the message runs, 95.8% of the participants knew about the message and, in the command runs, 86.1% of the participants knew about the command. 92.6% of these also executed the command. Over all runs, the information traveled an average of 34 seconds.

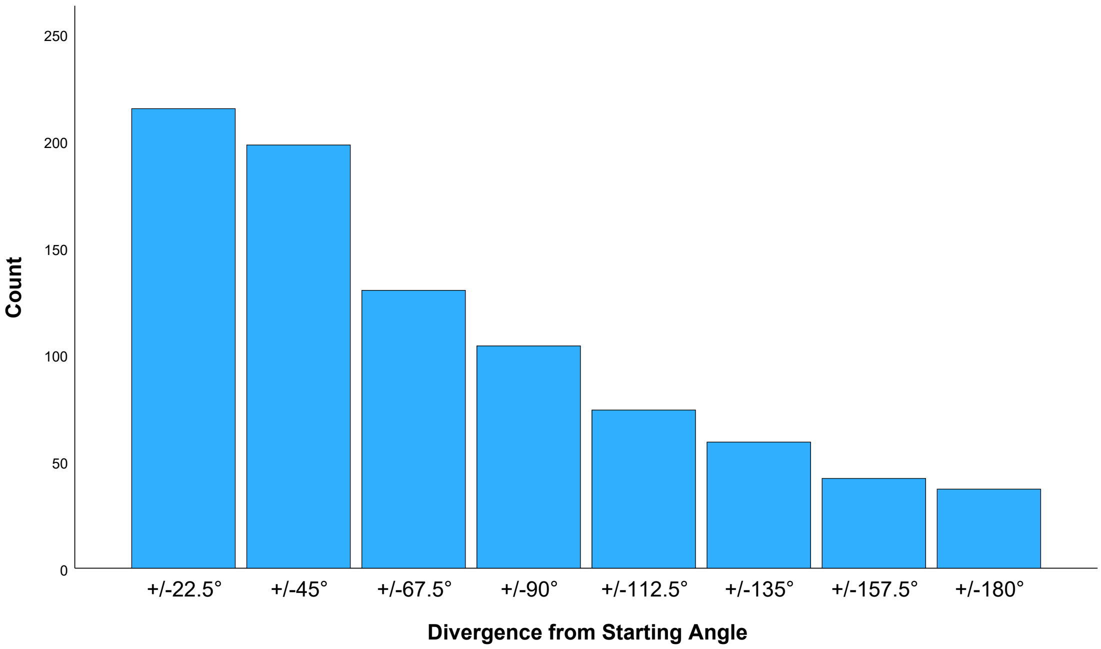

Figure 4 Frequency distribution of the divergence of the communication direction compared to the input direction (in angular degree). Almost 50% of the communication paths lie within a range of +/- 45° around the (intended) starting angle.

3.1.2 Direction of Information Transmission

As stated in section 2.4, we focused on verbal communication for the identification of the direction of information transmission. Since there was one run in which the command propagated almost exclusively visually, this run was excluded from this analysis. Thus, 32 runs were included (5 surprise and 27 interruption runs), in which – after deducting the 32 input directions given by the experimenters – 859 communication paths were identified. This number also includes information paths where participants were informed twice or more times. The frequency distribution of the communication directions relative to the angle of the information input is shown in Figure 4. In summary, the information often traveled more or less in the direction it came from, as 48.1% of the communication paths lay within a range of +/- 45° around the (intended) starting angle and 63.2% within a range of +/- 67.5°. If the range was broadening to +/- 90° around the start angle, it included already three quarters of all communication paths (i.e., a change of direction of max. 90°) and only in 24.7% of the cases the direction was completely changed.

Overall, the direction of communication did not change that often, what cannot be seen in the diagram but can be seen in the pictures with the directional arrows (Figures 2 & 7). In other words, it happened that information was passed on in a (completely) different direction than the one it came from. However, this new direction was then also temporarily maintained. Sometimes, these changes in direction occurred for no apparent reason, while other times they happened because someone shared the information with two or more par-

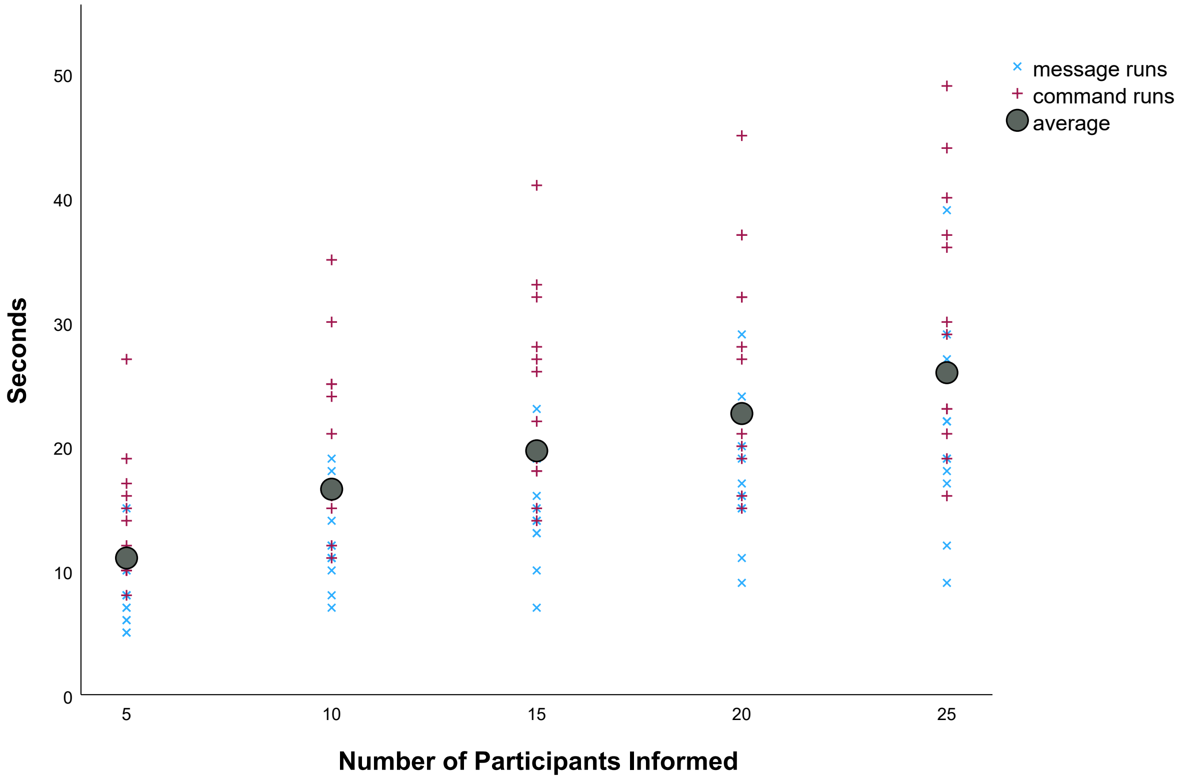

Figure 5 Time (in sec) until 5/10/15/20/25 participants received the information. Within one category, each cross represents one run. Each run is depicted in each category indicating the time needed in this run to inform the respective number of people. Overall, a linear relationship between the number of people informed and the time needed is shown.

ticipants (with only one standing in the previous direction) or because no one was left in the previous direction (i.e., at the border of a group). Following this observation, it is generally compelling to investigate what happens to information when reaching the border of a group, as it is then impossible to continue propagating in the previous direction. This is, of course, particularly important for smaller groups. Unsystematic observations of our data revealed that, on the one hand, the aforementioned changes in direction occurred. On the other hand, this was often the point at which the information subsided.

3.1.3 Speed of Information Transmission

As the surprise runs were not comparable with the other runs in terms of speed, only the message and command runs were taken into account for these analyses. To explore how long it took for a certain number of participants to be informed, Figure 5 shows – color-coded for message and command runs – after how many seconds a specified number of participants received the information as well as the mean value per category. Since only in 24 of 28 runs at least 25 participants received the information, four runs (one message and three command runs) were completely removed from this diagram. Due to a correlation

	B	95% CI	β	t	p
(Intercept)	2.92	[1.28, 4.57]		3.67	.001
Kind of information	0.38	[-0.07, 0.84]	0.29	1.73	.096
Density	-0.35	[-0.77, 0.07]	-0.29	-1.70	.102
Sequence of runs	-0.15	[-0.29, -0.01]	-0.39	-2.27	.033

Table 4 Regression results using kind of information, density and sequence of runs as predictors. Only the sequence of the runs significantly predicted the transmission time.

between the transmission time and the probability of informing 25 people (r = -.67, $p <$ .001), keeping these runs would have led to a distorted representation otherwise. In other words, the categories with the higher numbers of informed people would have appeared comparatively faster – although they may not have been – simply due to the dropout of the slower groups. All in all, Figure 5 shows a more or less linear relationship between the number of informed participants and the time needed, meaning that on average, it took about the same amount of time to inform five people, regardless of how many already knew. Furthermore, it looks like the information traveled faster in the message runs than in the command runs as slightly more pink than blue crosses are placed above the average.

3.1.4 Determinants of Faster Propagation

For the following calculations, all 28 interruption runs were again considered. In order to get a first impression of the relationships between the transmission time and the kind of information, the sequence of the runs as well as the density, the correlations are depicted in Figure 6. The results showed a significantly negative relationship between transmission time and sequence of runs as well as transmission time and density, meaning the information traveled faster in later runs and in runs where it was denser, but not between transmission time and kind of information. The linear multiple regression model was also significant, $F(3, 24) = 4.41$, $p = .013$, $R^2 = .36$. However, only the sequence of the runs was a significant predictor of the transmission time. The predictors kind of information and density were not significant (Table 4).

3.1.5 Distortion of Information

So far, all analyses only considered whether a person has received information at all or whether a command has been executed altogether. This approach was chosen to determine general patterns of information propagation independent of the content. Nonetheless, it should not be ignored that information can also change when it is passed on. In our experiment, in two message runs and in four command runs, at least one person received the wrong information and/or executed the wrong command. For example, ”the color is yellow” became ”the color is green”, the incorrectly colored dot was removed, or, the most common error, people did not tap themselves, but others on the shoulder. This resulted in 5.1% (message runs) and 9.9% (command runs) of the participants who received the

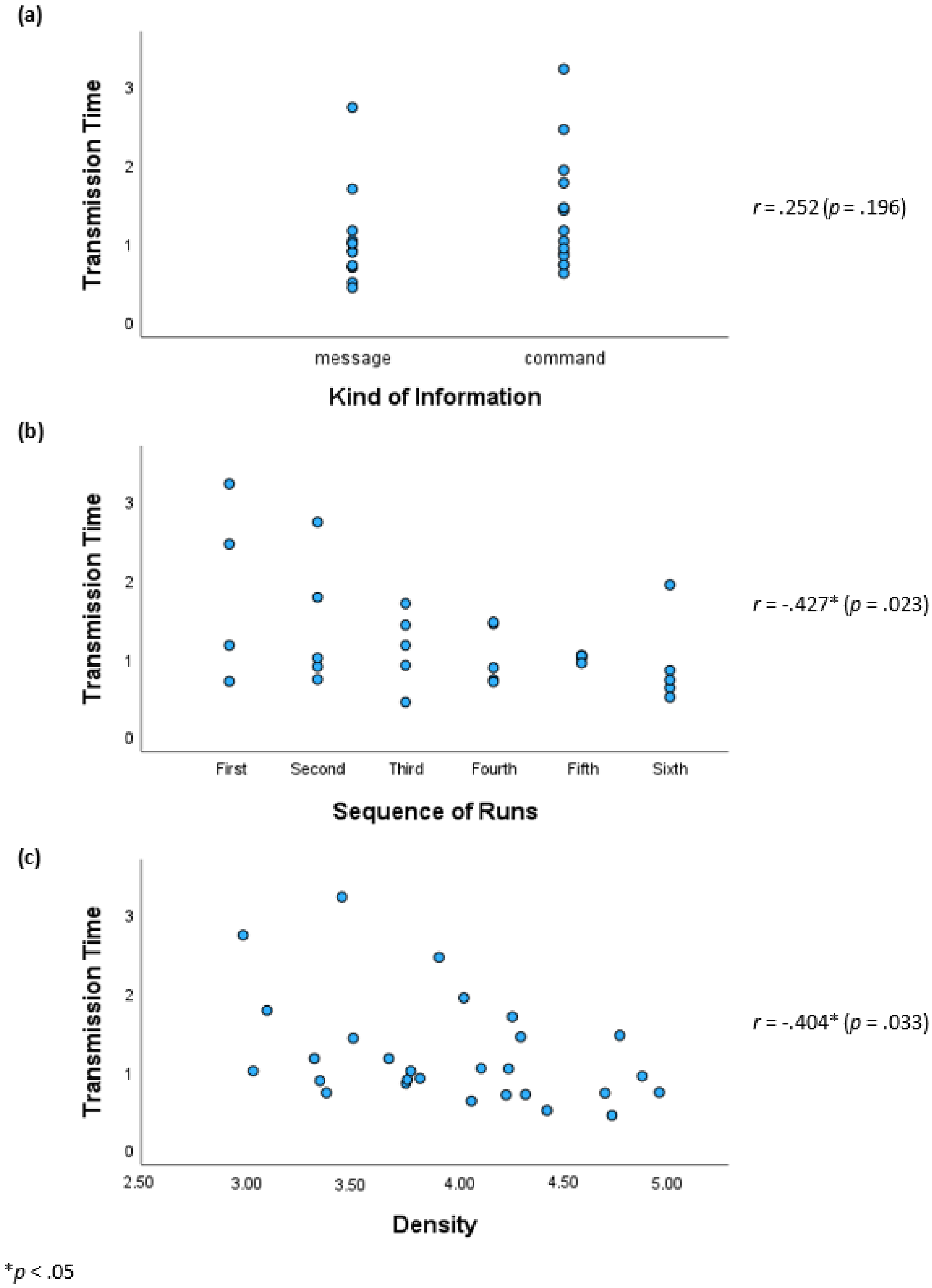

Figure 6 Correlation between transmission time (in sec) and (a) kind of information, (b) sequence of runs, and (c) density (in p/m^2). Each dot represents one run. There is a significantly negative correlation between the transmission time and the sequence of runs as well as the density, but not between the transmission time and the kind of information.

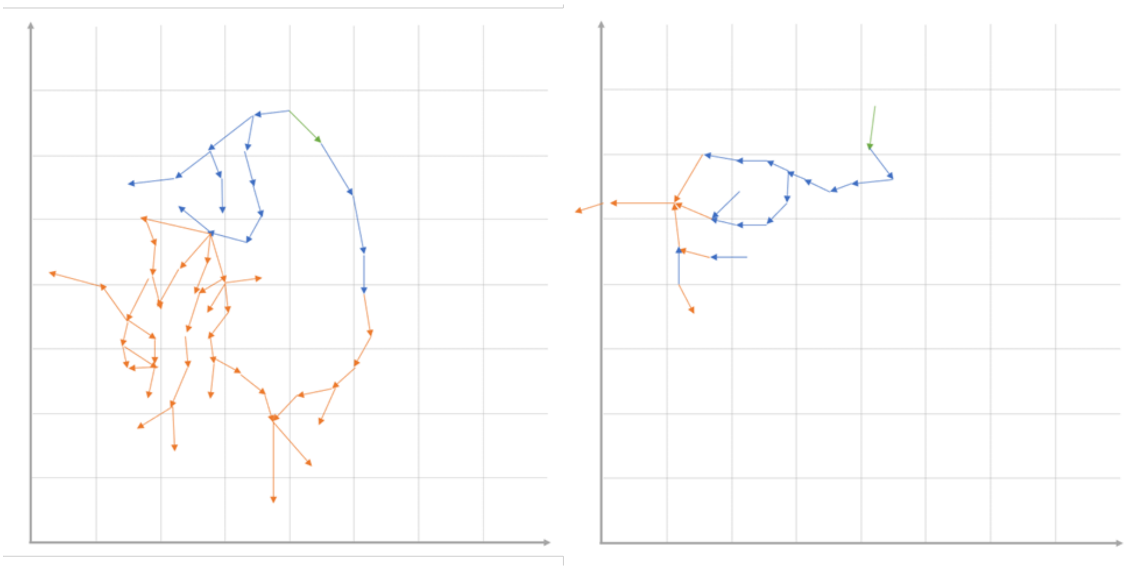

Figure 7 Direction of information transmission in the two runs of the Duesseldorf experiment. Figures are oriented so that the bottleneck is on the left-hand side (similar to Figure 2). The communication paths are indicated by arrows (green = information input, blue = first 15 communication paths indicating the initial propagation, orange = all further communication paths). The coordinate system is for visual orientation only and has no further meaning.

information being misinformed. Moreover, 9.9% of those who executed a command did so incorrectly.

3.2 Duesseldorf

The propagation of the command diverged moderately in the two runs of the Duesseldorf experiment (Figure 7), but the results overall supported the findings from the Wuppertal experiment. In both cases, the command traveled about 70 seconds until it subsided, but in one run 70 of 97 participants received it within this time (72.2%) and in the other run only 21 of 88 (23.9%). In the former, most of the participants followed the instruction correctly and put their hand on their own shoulder, but most of them also left it there. Seven participants first executed the instruction incorrectly and tapped on another person's shoulder, but later corrected themselves. In the latter, only the first person tapped on his/her own shoulder, whereas the remaining 20 tapped on the shoulder of another person (but removed it after a few seconds). The runs also differed with regard to the direction of information propagation. In the one where many people were informed, the command mainly traveled in the direction it started from (i.e., from right to left). From the 57 identified communication paths, 43.9% were within a range of +/-22.5° and two-third were within +/-45°, whereas the direction distribution of the 22 communications paths in the other run was less clear. Here, the orientation turned by 90° right at the beginning of the run (i.e., new orientation from the back to the front). Accordingly, almost two-third of the paths ranged from +/-45° to +/-135° while the others were distributed among the other directions.

4 Discussion

With our exploratory analysis, we were able to gain valuable insights on information propagation in crowds for crowd management and crowd research. First of all, our results showed that information propagation worked much better when people were aware of what their task is. Simply adding the instruction ”please pass it on” when inputting the information (as it was done by the experimenter in the surprise runs) did not work properly, not even in the relevant condition. In fact, in our experiment, the relevant information was passed on no better than the irrelevant information, even though the participants had already waited a minute without any information, did not know what was going on, and the possible explanation came from an authorized person (blue vest). The promoting effect of relevance suggested by the simulation of Hoogendoorn et al. [38] could therefore not be shown in our experiments. Overall, the fact that information propagation worked equally (poorly) in all surprise runs was an unexpected result. Indeed, the data suggests slightly that the propagation in the relevant condition was more constant over the three runs (both speed and number of participants informed), as in the irrelevant condition once many participants were informed quickly and once only a few participants were informed slowly. However, since there were only three and two runs, this result should not be over-interpreted and further investigation is needed.

In the runs where participants knew about their task, in contrast, they really wanted to fulfill it. This is evident not only from the high proportion of informed people in general, but also from the analysis of the communication paths indicating that some participants were informed several times and that some also shared the information more than once. Further, the videos show that participants actively looked around after receiving the information to check who might not have been informed yet. Nevertheless, it must be mentioned that there were of course also participants who did not comply and did not pass the message (13.3%) or the command (29.2%) on, nor executed it (9.7%). Moreover, participants got better during the course of the experiment. This was reflected in faster propagation.

Interestingly, even though not statistically significant, the message seemed to propagate faster than the command, for which two ways of propagation would have been possible (i.e., verbally and visually). This finding was contrary to our hypothesis. A reason could be that, according to the questionnaire, many participants only executed the command after hearing instead of seeing it (a fact that could also be verified by the videos) and the phrase to pass on tended to be longer in the command runs than in the message runs (e.g., “Peel the blue sticky dot off your shoulder.” vs. “The color is purple.”). Although many participants indicated to have both heard and seen the command (65.7%), the order could not be deduced from our data. So, it could either be that people only became aware of the command because they were approached by others or that they felt more secure about executing the behavior after hearing the spoken word (even though they might have seen the behavior before). The latter explanation also fits the finding that most participants executed the command only after several observations rather than after one. However, it must also be considered that the given instruction of playing ”whisper down the lane” might have left the participants feeling unsure, at least in the first runs, whether they were allowed to perform a behavior only on the basis of sight. Even so, latest after the first command run questionnaire, it should have been clear that this was a possibility since it was explicitly asked whether the command was executed upon sight. Additionally, in almost every run, there were participants who did so, even if they seemed to be more hesitant and looked around more to ensure themselves whether they were really doing the right thing. Only in one run, the command was transmitted almost exclusively visually, which resulted in one of the fastest command runs at 0.84 sec per informed person. This indicates that visual transmission might accelerate propagation but, in our experiment, it played a smaller role than expected.

A further finding was that the information changed in some of the runs (message as well as command). The command “tap yourself on the shoulder” seemed to be most susceptible since in two of the Wuppertal and in both Duesseldorf runs it became “tap others on the shoulder”. Additionally, the participants in one of the Duesseldorf runs who correctly tapped on their own shoulder mostly left their hand there for quite some time which was considered correct for our analysis but, speaking strictly, it did not correspond 100% to the original command. This command apparently being the one with the most room for interpretation can also be seen in the run in which it propagated mainly visually. In this case, all participants executed the command correctly but, in the questionnaire, they stated, e.g., “tap on green” instead of “tap yourself on the shoulder”. While all information presumably can change (e.g., in one run yellow became green), since some things sound similar or could be misunderstood, it is important to formulate messages/instructions with as little room for interpretation as possible. If the execution is additionally clearly visible to others (and perhaps remains visible for a longer time), there is a chance that individuals who were mistaken correct themselves or are being corrected by others (as in one of the Duesseldorf runs or in individual cases in Wuppertal, where participants first wanted to remove the green sticky dot when it should actually have been the blue one). In some cases, the participants even asked again or checked visually with others if they had understood the information correctly.

In general, participants did not seem to have a consistent preferred direction of communication, it was rather context-dependent. This is curious because it feels more effortful to communicate with the people at the front than with the people at the back, as the attention of the people at the front has to be gained first in order to be able to talk to them. In contrast, one only has to turn around to talk to the people at the back. In our experiments, however, it was mainly the case that the information traveled on in the direction it came from. Most of the time, this was the direction of the information input (i.e., if the information was given from behind, it tended to travel from the back to the front). However, if the direction of communication was changed for some reason (e.g., at the edge of the group), the new direction was also maintained for a longer time. This pattern was evident for the smaller groups in the Wuppertal experiment, but also for the larger group in the Duesseldorf experiment.

Concerning density, we saw at least on a correlative level what Zou and Chen [35] already assumed in their model: a higher density led to a faster propagation. Nevertheless, the maximum density reached in the Wuppertal experiment was about 5 people/m^2, which is only about half of the local densities reached in critical crowd situations (e.g., 10 people/m^2 in the Mina crowd disaster (Mecca, Saudi Arabia, 2006) [43]). As stated at the beginning of this paper, we assume an inverted u-shaped relationship between density and speed of information propagation, since reports of real life scenarios indicate an impeded propagation in very dense crowds [17, 18]. In this regard, however, further research on the exact mechanisms is needed. Besides the fact that human senses might become more limited the closer people stand to each other, it also becomes more difficult to turn the upper body and people's attention in these situations may be focused more on themselves than on their surroundings (e.g., out of fear of losing contact with the ground).

Overall, based on the results of this study, the idea that a piece of information (e.g., a rumor) can trigger a crowd accident must at least be questioned. If people were not clearly instructed to inform others, propagation was slow and only a few received the information at all. If they knew about their task, on the other hand, the transmission worked much better, but nevertheless the information often subsided without everyone receiving it. The imitation of behavior also seems to have a smaller influence than initially thought, as most participants executed the command only because they were told to, not because they saw it in others. Moreover, if someone performed the behavior because s/he saw it, the performance was also usually more hesitant. Interestingly, this all happened despite the experimental setting in which the participants should have known that this kind of special behavior could be part of the run – at the latest after the first command run.

At this point, however, the difference between experiment and reality must be pointed out, since a potentially life-saving behavior in a life-threatening situation (such as climbing stairs or poles) probably offers a greater incentive for imitation than pulling a colored dot off the shoulder. In general, the relevance of information in real life scenarios – especially in critical ones – is clearly higher than e.g., technical problems in an experiment. Thus, the incentive to inform others may also be higher. However, in these situations, other constraints could impede the information transmission, such as background noise. Although it is unlikely that people in an emergency will pass on the information quietly, but rather shout, as at the The Who concert [17], there is also much more noise at a concert than in our experiment. In our case, raising the voice was very effective, as shown by the run that was excluded from the analysis, in which suddenly many participants received the message at the same time, presumably because someone had spoken louder. But even though we tried to break the silence by playing some crowd noise, it is probably so loud at large-scale events that even shouted information can only be heard and understood by the nearest neighbors. From a psychological perspective, a further constraint comes into play: In order for people to pass on information or imitate a behavior, they must perceive the source of information as reliable and assume that this person knows more than they do. This is also consistent with the finding of Haghani and Sarvi [44], which showed that people are more likely to follow others in an evacuation scenario when they themselves have less information about the exits. In our experiment, this should indeed hold true, since the participants knew that others might receive information at some point, whereas in reality this is not necessarily the case.

4.1 Practical Implications

On a practical level, our results show that person-to-person information sharing could be used for crowd management, as a supplement or when other technical information systems fail. However, this strategy cannot be taken for granted and some issues need to be considered. For example, people do not necessarily share information just because they are asked to do so in the situation. It is important to clearly declare the passing on as people's task right from the beginning in order to promote commitment and thus the likelihood of compliance. This could be achieved, for example, by addressing all visitors at the beginning of an event and informing them that person-to-person communication might be used in case of emergency. Such a global announcement would also be beneficial because people are then more likely to perceive others as a reliable source, as it is plausible that they have more information. At the same time, it must be ensured though that this mechanism is not abused and people deliberately distribute misinformation. Besides the risk of intentional propagation of false information, information can also easily change when it is passed on. However, this can at least be reduced by using short and unambiguous phrases. Generally, it would also be useful to train visitors in passing on information, which will probably not be possible at a single event. But if this strategy of information transmission becomes standard in crowd management, it is possible that the entirety of event visitors will improve over time.

4.2 Limitations and Further Research

Overall, we had a large number of people participating in our experiments ($N = 375$), but the individual experimental groups were rather small. In the main experiment in Wuppertal, they comprised only 33 to 41 people, and even if our main results were confirmed by the two runs with a larger group (Duesseldorf experiment), approx. 100 people is also a small number compared to large-scale events. It therefore remains to be investigated whether the findings on the systematics of information propagation obtained here apply to crowds of several thousands as well. In addition, we also had comparatively few runs. With only five surprise runs, 28 runs with a small group, and two runs with a large group, a purely descriptive analysis was more reasonable in most cases, and the conducted statistical tests must be treated with caution. Even though we found a consistent significant result (i.e., the influence of the sequence of the runs), other influences were inconclusive and only tendencies could be shown (e.g., message vs. command runs). It remains to be seen if the findings will be confirmed in a larger number of runs and if the tendencies prove to be true. To further examine the relationship between density and information propagation, runs with more variation are also necessary since the density in our experiment ranged only between 3 and 5 people/m^2. In addition, the investigation of other influencing variables such as the side of the information input on the propagation speed would be interesting for further research, as in our study we had too few runs per side to calculate a reliable analysis.

Another limitation is the usage of paper and pencil questionnaires in the time-limited situation between runs which may have affected the quality of our data. This can be seen in missing data, discrepancies between questionnaire data and video observations, or even inconsequential answers within individual questionnaires (e.g., command only heard, but then also seen in three to four persons). With computer-based survey methods, at least this inconsequence could have been prevented, since certain answer combinations could have been excluded per default. However, this type of survey was not feasible in our experimental setting. Some parts of the questionnaire may also have been too complicated (e.g., if the behavior was performed based on seeing it, was it due to one or several observations) or it was generally difficult to reflect the own behavior in retrospect (e.g., did someone perform a behavior upon seeing or hearing). The questionnaire methodology should therefore be improved in a subsequent study. However, as our analysis included not only the questionnaire but also the video data, we were able to support our main findings with observations, which is at the same time a strength of our study.

Lastly, we investigated the question of information propagation in crowds solely in an artificial, laboratory environment. However, as discussed above, the general conditions at a large-scale event might be quite different from those in an experiment (e.g., higher relevance of the information, but noisier). Therefore, field studies are needed to generalize our results and see if our advice proves helpful for crowd management in real-life situations.

5 Conclusion

To the best of our knowledge, this study is the first to systematically investigate information propagation in crowds. Our initial findings show tendencies that there is no preferred direction of communication, but that information travels mainly in the direction it comes from, that the spoken word has greater influence than a seen behavior, and that a higher density contributes to a faster propagation. Above all, it has been shown that it is not that easy to propagate behavior or messages in a crowd, but that it is possible to train people and increase the likelihood of sharing.

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Ethics Statement Full ethical clearance for both experiments was granted by ethical review committee of the University of Wuppertal, Germany. Written and informed consent was obtained from all participants who took part in the experiments.

Author Contributions Helena Lügering: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization / Anna Sieben: Investigation, Writing - Review & Editing, Supervision

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Data Availability. The video recordings and head trajectories for both experiments as well as the questionnaire data for the Wuppertal experiment are available through the Pedestrian Dynamics Data Archive hosted by the Forschungszentrum Juelich, doi:10.34735/ped.2022.5.

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