NETWORK SCIENCE AND CROWD BEHAVIOR METRICS

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ABSTRACT

ARDEC's Target Behavioral Response Laboratory is currently conducting research on methods for crowd laboratory experiments, specifically crowd behavior metrics. Crowd metrics based on topological data were derived using motion capture methods. Sociometrics were based on coded videotaped communications. The preliminary results suggest that these crowd metrics, including those produced by network science methods, should be considered for further study. The results also suggest that crowd metrics, rather than only weapon characteristics, should be used to compare effectiveness of non-lethal weapons from different technologies.

1. INTRODUCTION

1.1 Non-lethal Weapons and Systems in Crowd Situations

In military operations other than war and stability and support operations, soldiers may be faced with problems of managing crowds of people engaging in non-peaceful demonstrations, public disorder, and riots (Headquarters, Department of the Army, 2003, 2004, 2005). To prevent and manage possible civil disturbances, new weapons, in particular non-lethal weapons (NLW), and the tactics, techniques, and procedures (TTPs) for their employment need to be developed. However, to accomplish these goals there must be a basic understanding of crowd behavior and a way to judge and compare the effectiveness of NLW or TTPs.

This paper presents the preliminary results of ongoing data collection on crowd behavior at the Target Behavioral Response Laboratory (TBRL). The crowd research program was designed with three distinct phases (Mezzacappa, 2008a). The first is the development of reliable and valid methods and metrics for initial crowd characteristics and crowd behavioral response, followed by programmatic research of the conceptual model of crowd behavior in the laboratory, followed by high fidelity testing outside of the laboratory.

The sequence was proposed based on the logic that experimentation using quantitative methods requires that variables (such as crowd response) be measurable, hence it requires methods to reliably perform measurements. The problem being addressed in the first phase of the TBRL crowd program is to develop a methodology that can reliably, repeatedly and validly measure the independent and dependent variables relevant for investigations of crowd behavior. That is, the task is simply to devise methods to create analyzable crowd data.

The paper begins with a review of the literature on crowds and small groups with a focus on measures and metrics indexing their characteristics. A conceptual framework that is particularly suited for guiding experimentation on effectiveness is described. Next, the results of the current methodology will be described with examples of collected measures.

1.2 Crowd Behavior

The peer-reviewed literature on crowds exists in several disciplines, each with different measures and metrics of interest. For example, within sociology, much of the early work focused on description and analysis of the "madding crowd" and "mass hysteria" (Brown 1954; McPhail 1991; Miller 2000). Measures included demographics and characteristics of those who participated in riots and mobs. More recent sociological work on crowds focuses on describing the life cycle of crowds and categorical descriptions of collective and individual behaviors in crowds (Wohlstein and McPhail 1979; McPhail and Wohlstein 1983; McPhail and Wohlstein 1986; Schweingruber and McPhail 1999; McPhail and Tucker 2003). Social psychology, in particular the subdiscipline of group dynamics, focuses primarily on controlled laboratory experiments on such topics as conformity pressures (Asch 1951; Festinger 1954), group structure and processes, and communication (Bavelas 1968), and intergroup conflict (Deutsch 1973).

More recent computer-based investigations on pedestrian traffic flow, emergency egress, and stampeding (Fang, Lo et al. 2003; Fang, Yuan et al. 2008) are also of interest to the crowd behavior researcher. Riot control (on campus, at sports and entertainment events, civil unrest) by police forces is another area of attention (Madensen and Eck undated; Russell and Arms 1998; Russell 2004). Although crowd behavior research is relevant to military missions, the DoD literature is silent regarding scientific investigations of crowds.

To date, the metrics that could be derived from previous investigations are for the most part unsuitable for the question of weapon effectiveness in crowd situations (Cooke et al, 2007). Crowd level metrics are needed to characterize and quantify possible psychosocial crowd characteristics such as group cohesion, authority structure,

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14. ABSTRACT
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flow of information that determine crowd behavior. Moreover, crowd level metrics are needed to quantify individual and crowd behaviors in response to stimuli, including non-lethal stimuli as part of an escalation of force concept.

New measures and metrics are needed. An examination of commands typically given to crowd members involve controlling their whereabouts—“Stay back!” “Leave!” or “Stay!” Therefore, it is proposed that evaluation of NLW effectiveness should be based on how well use of the weapon can control location and movement of crowd members. Following from this reasoning, research methods were designed to develop novel measures and metrics of crowd location, and movement from location to location (“locomotion”).

2. THEORETICAL FRAMEWORK

In order to adequately characterize a crowd comprised of multiple individuals, two aspects must be considered. The first is the behavior of the individual and those forces which guide behavior within the environment. The behavior of a crowd cannot be described by aggregation of individual data alone; the social network characteristics describing how the multiple individuals interact with each other must also be considered. Therefore, the theoretical framework used for this study is based on two complementary approaches to describe the complete situation: Lewinian Field Theory and Social Network Analysis.

2.1 Topological Psychology and Field Theory

Based on the determination that location and locomotion are the primary variables on which to base evaluations of effectiveness, a conceptual framework that can be used to make predictions about location and locomotion was adopted for the program of research on crowd behavior. The conceptual framework for this program of research is based on field theory as articulated by Kurt Lewin (also known as topological psychology). The primary tenets of this orientation is that individual behavior is purposive and goal oriented, guided by social, psychological, and environmental factors; and that mathematical concepts could be used to describe, understand, and predict behavior.

More formally, as Lewin’s famous equation states: Behavior (B) is a function (F) of the person (P) and of his environment (E): **B=F(P,E)** where the state of the person and that of the environment are not independent of each other. To understand or to predict behavior, the person and the environment must be considered as one constellation of interdependent factors. Of critical importance is the concept of goals, psychological goals such as “maintaining honor” or physical goals or destinations such as “getting to the American checkpoint.” A person exists within a field of attractive and repulsive forces toward and away from goals. These forces generate behavior toward achieving those goals. An adequate description of field theory is beyond the scope of this paper, please see collections of Lewin’s major works, particularly Field Theory in Social Science (1948) and Principles of Topological Psychology (1936).

The strength of the theory is that it deals directly with predictions of locomotion or physical movement through a space. Therefore, this theory can be used to design experiments to identify factors relevant to effective tactics of halting approach, area denial or clearing, and maintaining standoff distances.

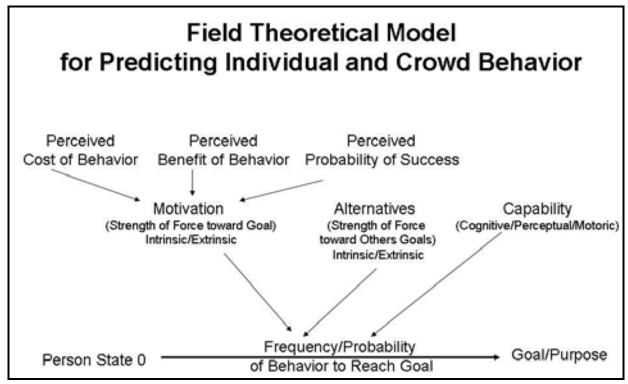

Figure 1: Conceptual framework for TBRL’s crowd behavior research program.

A basic theory of crowd behavior has been developed based on the field theoretical tenets. Figure 1 represents the TBRL’s conceptual model of the mechanisms by which a non-lethal system may affect behavior of individuals in the crowd and the crowd as a whole. (Please see Mezzacappa, 2008a for a more complete discussion of this theoretical model). Experiments have been designed based on this conceptual framework.

To summarize the model, whether or not a person performs a behavior toward reaching a goal depends on the level of motivation, the presence of alternative behaviors, and whether or not the capability exists for the performance of the behavior. In addition, motivation is affected by the perceived costs, benefits, and probability of success of the behavior. The perception of the costs (or punishments), the benefits (or rewards) and the probability of success are shaped by the social environment as well as the individual’s experience.

As an example, whether or not Johnny throws a rock at Blue depends on how badly he wants to annoy Blue, whether or not there is another way to annoy Blue, and whether there are any rocks lying around. Rock throwing also depends on how likely Johnny believes he will be punished, what good it will do to hit Blue, and how likely he believes he will hit Blue. His belief will be affected by what he sees when the others around him throw rocks and what happened to him the last time he threw rocks.

2.2 Social Network Theory

The behavior of individuals is influenced by their connections to other individuals in a group. These connections can either be social (friends, family, co-workers) driven by homophily (having the same attribute) or simple proximity (the strangers next to you) driven by propinquity (being at the same place at the same time). The methods of network science may be useful tools in characterizing and quantifying psychosocial crowd characteristics. The origin of the science of network analysis was in the analyses of groups of persons and the relationships among them, that is, social network analysis (Wasserman & Faust, 1994; Carrington, Scott & Wasserman, 2005). Therefore, since the method was fundamentally developed for understanding groups of people, it is not difficult to imagine that these methods may be useful in studying crowds that the Warfighter might encounter.

The structure of a network is specified by indicating which nodes are linked to other nodes. In studies of groups of people or crowds, the nodes are people and the links are their relationships or interactions. Within social network analysis, relationships may be psychosocial (as in cohesive bonds between crowd members) or physical (as in distances between crowd members and control force members). The outcomes of social network analysis are indices of characteristics of crowds (e.g., how much intercommunication occurs, how cohesive), roles of persons in the crowd (e.g., influential persons, isolates).

Given that part of crowd threat assessment includes listening to communication among the crowd, as well as identification of leaders or instigators, the tools of social network science should be investigated in crowd behavior research. Measures such as closeness, betweeness, radiality, structural cohesion, and many others can be adapted for investigations of crowd behavior; however, the specifics of these network analysis metrics are beyond the scope of this paper (see Carrington, Scott & Wasserman, 2005; Wasserman & Faust, 1994)

3. METHOD

The data were drawn from a larger study on crowd response to simulated NLW (please see Mezzacappa, 2008b for more details on the full study). All methods used in this study were approved by the local research ethics board at the Armament Research Development and Engineering Center (ARDEC). Subjects were recruited from the general public and paid $20/hour for participation. Procedures were carried out in the TBRL Crowd Behavior Testbed. Crowds were comprised of 12 subjects each.

After informed consent was obtained, subjects performed a task that simulated the tactical construct of a crowd facing an area protected by a control force. The behavioral construct ("Halt Crowd Approach") is a condition where the crowd approaches the protected area, and the control force attempts to stop their approach. The control force members (drawn from the research team) wield either hand-to-hand combat weapons or stand-off projectile weapons. Measures capturing the two aspects of crowd behavior, the behavior of the individual and the social network, were recorded and assessed.

3.1 Individual Methodology

A Lewinian constellation of forces was imposed on the subjects through the creation of attractive (rewarding) and repulsive (punishing) forces. In this study, the subjects were given a goal with an associated reward and were presented with a hindrance and an associated potential punishment.

Subjects were tasked with throwing "rocks" into targets on a M1008 Commercial Utility Cargo Vehicle (CUCV). Each successful throw was awarded points and dollars for the group. Following from the theoretical model, these points are the "perceived benefit" associated with the goal to create the subject's valence for the goal.

The armed control force stood between the crowd and the CUCV. Subjects also were tasked with avoiding being hit with the hand-to-hand combat weapons and the projectiles from the stand-off weapons. Ends of batons and projectiles were chalked to mark impacts on subjects. Each chalk mark was penalized by loss of points and dollars for the group. Following from the theoretical model, these points are the "perceived cost" of approaching and create the subjects' negative valence to being hit[1]. If subjects are chalked before throwing, they forfeit the throw, that is, they cannot gain dollars or points. If they are chalked after they throw, they are still penalized. After each trial, subjects returned to the start line.

Robustness of the methodology was checked through providing several environments varying ease of approach. This was done by varying the number of persons on the control force and by varying the weapon. There were two conditions for Number of Control Force: One (high probability of success of approach) and Three (low probability of success). There were two conditions for Range of Weapon: Stand-off (lower probability of success because of longer range) and Hand-to-Hand

[1] Punishments and rewards could be varied for future experiments. For example, to simulate the mindset of a "martyr", the size of the reward relative to the punishment could be altered or being hit by a weapon could be greatly rewarded with no valence for the goal. That is, a martyr feels rewarded for suffering.

Combat (higher probability of success because of relatively shorter range).

Two rules of engagement were also used to guide the behavior of the control force. In the No Threat condition, control forces were instructed not to chalk the subjects; in the Threat condition, control forces were instructed to chalk the subjects. Subjects were unaware of the condition for each trial, but could quickly deduce whether or not they would be chalked during the trial. Therefore a 2x2x2 within subjects factorial design was employed with the two levels each of Weapon (Hand-to-hand or Stand-off), Number of Control Force (One or Three persons), and Threat (No Threat or Threat).

Note that the perceived probability of success is likely to be less and the perceived cost of the behavior is likely to be greater in the second compared with the first levels of the variables. Therefore, based on the conceptual model, less approach behavior (e.g., crowd stays farther away or delays approach) is expected in the second level compared with the first.

In addition to the stimuli conditions, a baseline condition was run where subjects were throwing into the targets with no control force present. After a series of runs which simulated an escalation of force, the order of conditions was randomized.

3.2 Individual Measurement

A Vicon V8i Motion Capture (MOCAP) system (www.vicon.com) was used to capture detailed movement data of crowd members across a 40 foot x 32 foot area. The system uses sensors that track reflective markers worn on the subjects to track six degrees of freedom (6DOF) motion in three dimensions through time. This device allows recording of orientation, location, and movement of each person in the group. These data were recorded on the subjects and control force throughout all trials.

Custom software was created to reduce the raw Vicon data into a useable format of XY location and orientation of each subject and control force member which was then reduced to 30 frames of data per second. A MathCAD worksheet specially developed by TBRL was then used to calculate measures and metrics for analysis.

A set of possible crowd measures and metrics was proposed, including the mathematical definitions required for calculation. Planned measures from other DoD programs using simulations to study crowds were used as a starting point (Aegis Technology Group, 2007) and additional measures were developed based on engineering methods for solid and fluid mechanics[2]. Individual state metrics to describe the condition of each crowd member at an instant in time included instantaneous velocity and the distance between every pair of subjects. Crowd level state metrics that describe the group as a whole included geometric center and centroid, the area occupied by the crowd, density, bulk velocity and many others. Interaction metrics that describe how the crowd and the control force interact included distance between each control force member and each subject, minimum distances between crowd members and the control force. In the future, when the full complement of data are collected, the sensitivity, specificity, and discriminant ability of each of these measures will be compared. Based on the results of these comparisons, this list will then undergo down selection to identify suitable crowd metrics that accurately reflect a particular situation and precisely reflect differences between disparate situations.

3.3 Social Network Methodology

During these tasks, all 12 subjects were videotaped using 6 standard cameras mounted on overhead trusses. Two epochs of time from their experimental sessions were chosen. The first epoch occurred at the beginning of the session following the very first attempt at the tasks. The second epoch occurred at the very end of the session, following the very last trial of the tasks. Therefore, the data analyzed consists of communication behaviors in two crowds, at the very beginning of the session and at the very end. This provides information about the social interaction network when the crowd first formed and then after the individuals had existed as a crowd for a period of time.[3]

The videotapes were coded for presence or absence of social interactions between each pair of the 12 subjects. A social interaction was defined as 1) verbal communication, 2) physical contact ("high-fiving"), 3) gestures toward another member ("thumbs up sign") 4) non-verbal auditory signaling (clapping). The resulting 12 x 12 adjacency matrix was entered into a networking analysis software package (ORA Version 1.9.5.2.9., http://www.casos.cs.cmu.edu). This package was used to generate tables of sociometric data (number of subgroups, isolates, number of linkages among nodes) which then are crowd metrics that could be entered into analyses, as well as visualization of the nodes and linkages.

The distance analyses derived from the MathCad computations discussed above were also submitted to

[2] Concepts from mechanics were only used to develop measures of the state of the crowd. It is not proposed that members of the crowd follow the behavior of particles.

[3] In the future it is proposed that multiple epochs throughout the session be used to see how the social network evolves over time, such as between each trial.

further network analyses using the ORA software. The distance adjacency matrices were entered into the program. As output, network visualization techniques were used to graph the distances between the control force team and subjects for one frame of data in the initial stages of an experimental run. A single frame was used in this analysis to demonstrate the method, which could easily be repeated on any number of frames in future studies. Network analysis of the distance adjacency matrix provides information about members of the crowd who move together or remain in close proximity through the trial.

4. RESULTS

4.1 Topological Results

Tools and methodology were successfully created for calculation of crowd behavior metrics from the collected data. Because data collection has just been initiated in the results that follow, only case studies of crowds are presented. In other words, these results should not be construed as outcomes from standard tests of significance. Rather they are demonstrations of the metrics and measures, and demonstrations of their face validity in how they reflect the crowd situation. When the full complement of subjects is run, proper F statistics, df's, confidence intervals, effect sizes, and p-values can be reported, including those appropriate for group-level statistical analyses (Moritz and Watson 1998; Pollack 1998)

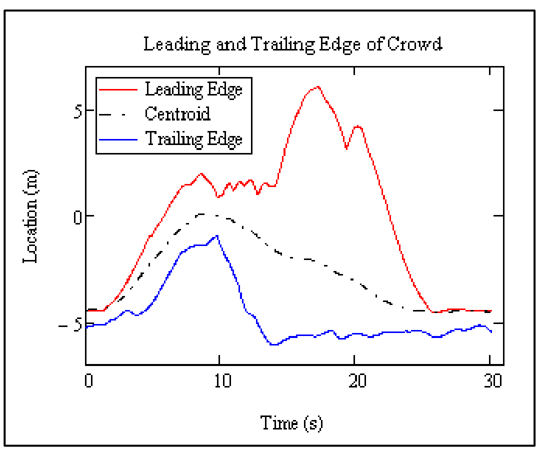

Figure 2: Movement of leading and trailing edges of the crowd toward goal; higher on the y axis indicates closer to the CUCV.

Figure 2 represents data collected from a single crowd event. The leading and trailing edge represent the front to back extremes of the crowd (toward and away from goal) and the centroid represents the bulk of the crowd. In this example the goal is towards the top of the graph and the start/finish line is the bottom of the graph.

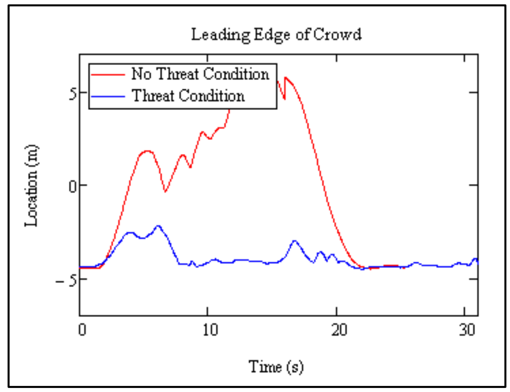

Figure 3: Movement of the leading edge toward goal under Threat and No Threat conditions; higher on the y axis indicates closer to the CUCV .

Such metrics can also be used to compare conditions. For example, Figure 3 shows the leading edge of a crowd under Threat and No Threat conditions. The figure supports the prediction based on the hypothesis that there will be less approach behavior in the threat compared with no threat condition.

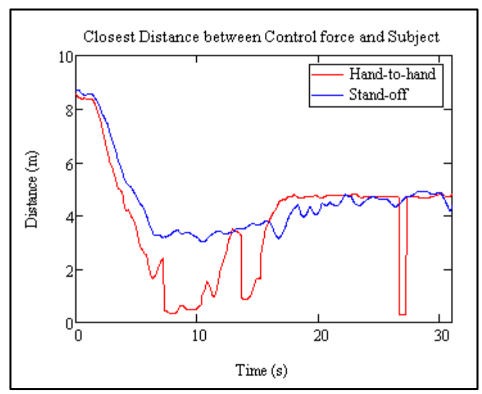

Figure 4: Distance between crowd members & control in Hand-to-hand and Stand-off conditions; higher on the y axis indicates further distance.

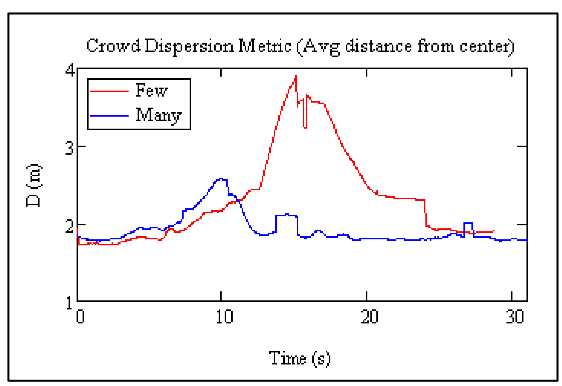

Figure 5: Crowd dispersion under Few and Many conditions, higher on the y-axis indicates greater dispersion.

Combined measures are also created, such as Figure 4 which shows the closest distance of any subject to any control force member over time. The figure supports the prediction made by the model that crowd members will approach closer when the control force uses hand-to-hand weapons compared to stand-off weapons, where crowd members maintained about three meters of stand-off from the control force.

Measures also were calculated to describe the overall condition of the crowd. Figure 5 shows how the crowd dispersion metric changes over time. This is a measure of how spread out or how clustered the crowd is. The figure supports the prediction based on the hypothesis that compared with fewer control force, the control force with a greater number is better able to contain the crowd (i.e., decrease approach behavior). In the condition with only one person on the control force, the crowd becomes more dispersed as some members are held back while others continue around the control force on both sides, spreading out.

Although the results were not the outcome of formal statistical analyses, the simple comparison of the graphs derived from actual data support two notions: first, that the calculated metrics are sensitive to crowd situation and can be used to measure and distinguish between different scenarios; and second, that these metrics can be used to test the theoretical model. These graphs are only a sample of the measures calculated to demonstrate the success of the method to measure the crowd's behavior.

4.2 Network Analysis Results

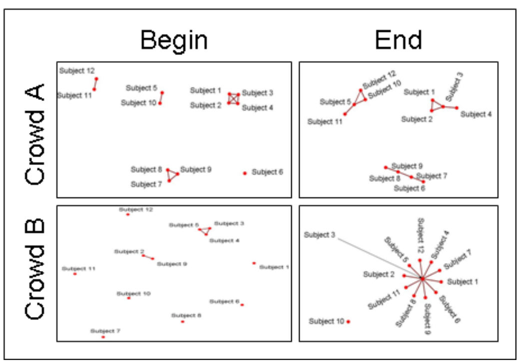

Figure 6: Visualization of social communication networks of two crowds at beginning and end of session.

Data from each of the four epochs were rendered into 2D network figures using the ORA visualization function (Figure 6). Each subject is represented as a node in the network, and presence of a communication is represented as a link. As indicated by these preliminary visualizations, crowds may initially differ significantly in these group level sociometrics in terms of communication linkages. In addition, these crowd metrics change over time. It is possible that over time, or through shared experiences, certain patterns of network structure may emerge.

Moreover, quantitative crowd level group metrics of social communications were derived (See Table 1). Number of nodes, linkages, and density (# linkages/# possible linkages) are quantitative crowd level metrics that can be submitted to statistical analyses and can be interpreted probabilistically. That is, not only can the visual representations give researchers insight into crowd behavior, but the numerical outputs from network analysis can be submitted to formal statistical analyses as either independent variables (initial crowd state) or dependent variables (crowd response).

TABLE 1: CROWD LEVEL SOCIOMETRICS

	CROWD A		*CROWD B*	
Variable	Beginning	End	Beginning	End
Node Count	12	12	12	12
Link Count	22	21	8	20
Number of Subgroups	4	4	2	1
Number of Quads	1	4	0	0
Number of Triads	1	0	1	0
Number of Dyads	2	0	1	0
Number of Isolates	1	0	7	1
Density	0.1667	0.1591	0.0600	0.1515

For example, one research question may be how should crowd composition affect weapon selection or TTPs? Responses to NLW may differ between a crowd made up of mostly isolates, such as crowds of people who have no interrelatedness beyond being at the same place at the same time, and crowds who are made up of mostly subgroups, such as families. Questions such as these may now be asked using the sociometrics derived from network analysis.

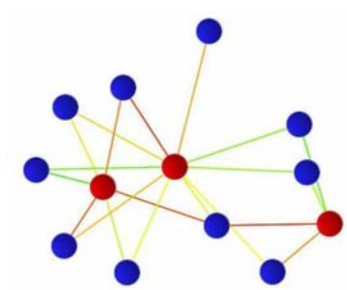

Figure 7: Visualization of control force (red) to subject (blue) at distances less that 6.5 m (chosen for illustrative purposes).

Proximity data from the adjacency matrices were also rendered into 2D network figures (the quantitative metrics discussed above are also available). Figure 7 shows the results of network science techniques of visualization on the distance data. In this network, distances among each of the 3 control force (red circles) and each of the 12 subjects (blue circles) were used. Proximity is indicated by the color of the linkages between nodes. Red indicates the closest proximity, yellow to orange, those in mid-range, and those in green, subjects that are farthest away.

These primary indices derived from social network analyses capture crowd characteristics that, based on our conceptual model, can be hypothesized to affect group behavior (such as social interactions) and those which should be affected by NLW (such as distances to control force). Thus, other network science types of group level metrics (centrality, betweeness, closeness) also should be investigated for their possible utility.

5. THE WAY FORWARD

To our knowledge, this is the first reporting of empirical data on crowd behavior that have been collected and analyzed under controlled laboratory conditions. With the development of these crowd measures and metrics, a wide variety of applied, practical, and tactically relevant questions can now be explored--Given a particular weapon or canalization tactic, at what distance from a control force will an individual choose to stop advancing? How fast does a group retreat at a given density? What sociometric structures correlate to what patterns of behavior? Using these data, the network structure and eventually dynamic functions of crowds can be investigated through analyses of behavioral links among the nodes of people.

The approach described in this paper is unique in that both behavior of the individual crowd member and the crowd as a whole are considered. Of particular interest is the network structure relating to behavior propagation through the crowd. That is, given that one person performs a behavior, how likely is it that others in the crowd will follow the behavior? More specifically, if one person runs away from the control force will others follow suit? If so, which others? The empirical data gathered from this experiment will be used to examine the behavioral links between the persons, thus establishing links among the nodes in the structure of the network. That is, correlations among behaviors of subjects will be calculated to identify nodes that are linked and the nature of those links (e.g., strong or weak, directionality, positive and/or negative correlations between individuals' behaviors). Because small groups of fewer than 20 persons are being tested, this might be called a focus on local structure. But, this identification may be useful in predicting crowd behavior in more complex larger gatherings.

The data gathered assist the study of concrete problems, for example, target selection. Target selection may be thought of as a task of identification of a node/person or subgroup, which is structurally an influential hub within the crowd network (See the central node that is Subject 3 in Figure 6, lower right panel). This hub may be considered a likely target in attempts at suppressing crowd approach.

Using network analysis methods, it may be possible to identify patterns of certain categories of sub-groups likely to behave similarly. That is, the methods may provide the ability to differentiate between ad-hoc groups of strangers, versus family and friends, versus organized militants. It is proposed that in the future these same techniques can be used to check for similarities of any of the topological measures discussed above. For example, it may be possible to identify that a cluster of individuals who are socially connected and who are also closely related in the way they move, perhaps advancing very close to the goal and doing so very quickly under all conditions. If such correlations are identified, then more detailed analyses may identify similarities or at least indicators of group structure.

Identification of these indicators has a direct benefit for the Soldier. In the future, network science visualization techniques can be used in threat assessment. One might speculate that the technology could be developed so that sensors that detect location, locomotion, and communication, together with network analysis algorithms could be developed to provide real time threat assessment in the field.

Finally, but most importantly, the results indicate that effectiveness research that focuses on crowd behavior (rather than just on weapon characteristics) has a valuable result. The focus on crowd behavior allows us to evaluate relative effectiveness of very different types of NLW. Comparisons of the effectiveness of different technologies is problematic because of the dissimilarities in physiological effect (for example, injury from blunt impact compared with heat sensations from a directed energy weapon). Effectiveness testing based on crowd response resolves that problem as it can be measured using the same metrics without regard to NLW characteristics. The equivalence of response allows comparison of the effectiveness of NLW of different technologies.

CONCLUSION

These preliminary results support the contention that empirical data gathered in the laboratory within experiments formed by field theory, when submitted to network analysis may provide useful measures that are descriptive and sensitive to the behavior of crowds. Therefore, they should be further explored for their utility for understanding and predicting crowd behavior. An understanding of methods and metrics of crowd behavior is needed in the development of effectiveness testing of NLW as well as the TTPs for their use in crowd situations. The data gathered and the analyses undertaken will assist in further developing non-lethal options for force protection in crowd situations.

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