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Simulating archaeologists? Using agent-based modelling to improve battlefield excavations

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ABSTRACT

The study of material culture generated by military engagements has created an emergent sub-discipline of archaeological studies centred on battlefields. This approach has developed a particular and sophisticated methodology that is able to deal with the fact that archaeologists will often not find either structures or a useful stratigraphical record on the site, as the material remains of the battle will basically be metallic objects carried by combatants. It is therefore rather complicated not only to test hypotheses about battle events based on archaeological data, but also to validate the methodology used. Here we propose the use of agent-based models to explore these issues in the case of eighteenth-century battlefield archaeology. The simulation is divided into four different steps. Firstly, a battle is simulated in order to generate realistic virtual archaeological remains left by an engagement between two armies of this era. We then simulate the loss of information that the passing of time produces in the battlefield. The third step involves simulating the archaeological survey, enabling us to explore different survey strategies and the impact on the interpretation of the event itself. Finally, we design a confidence index in order to compare the results of the different virtual excavations using spatial analysis and statistics. The results show that the methodology is fully functional in terms of understanding a battle, and it allows us to suggest new strategies to improve fieldwork and to develop new ways of exploring these particular archaeological sites. It is concluded that the described approach illustrates how simulation can be used to explore methodological issues of archaeological science.

1. Introduction: the excavation and interpretation of a battle

A battlefield is different to other types of archaeological sites, such as settlements, since it results from the concentration of thousands of human beings in a small, delimited zone during a brief period of time, usually one or two days. Consequently, no structures or any kind of stratigraphical sequence are usually available. Moreover, the area that must be studied is usually larger than other sites, it being in the order of 1–100 square kilometres (or even bigger, as in the case of Oudenaarde, 1708). Thus, although the methodology for dealing with battlefields is more related to standard archaeological field survey it will be shown that there are important differences due to the particularities of these sites. Furthermore, the discipline has relatively recent foundations, as the first excavations that led to the development of this particular archaeology were made during the 1980s' in the battlefield of Little Big Horn (Scott et al., 1989). In this paper we will briefly describe the different steps followed by almost all battlefield archaeological projects, in order to analyse the issues which can arise from them.

1.1. Fieldwork

Most of the material remains generated by a battle are metallic objects, such as bullets, weapons fragments, pieces of armour, etc., and this is why the identification of battlefield artefacts is based on the use of metal detectors. The key concept of the entire research process is the detection of spatial patterns in the distributions of these artefacts, and hence the aim of fieldwork is to locate and geo-reference metallic objects related to the battle. The choice of a particular technique to calculate positions will differ depending on geographical and environmental features, although it is usually based on the establishment of parallel transects that are followed by the archaeological teams. One of the most popular systems is the use of handheld GPS devices. Each archaeologist carries a GPS that automatically tracks the position of the team, as well as the exact

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location of each individual item collected. Another approach is the delimitation of transects and item locations using a single, more precise centimetric GPS technology, or more common techniques such as the definition of series of referenced squared grids.

This fieldwork will generate a collection of metallic items that the archaeologists will need to identify in order to establish whether they were deposited in the soil during the battle. If the battle took place after the introduction of firearms the finding of bullets will be extremely interesting as their analysis will provide valuable data about the intensity and direction of combat (Sivilich, 2005). Further interpretations of the archaeological evidence will be useful to understand the characteristics of the armies that were engaged in the battlefield (i.e. weapons used by the combatants, degree of standardization of their equipment, presence of military units with identifiable objects such as insignias, etc.).

1.2. From data to knowledge

The second phase of the methodology is the processing and refinement of gathered data in order to generate hypotheses about the development of events. The methodology has benefited from the introduction of geographical information systems (GIS) into archaeology, as these are an excellent tool to analyse collected information and to plan future fieldwork. On the one hand, GPS tracks can be loaded into a GIS project as a way of delimiting the areas of the battlefield that have been explored. On the other hand, the team will be able to create a database with the entire collection of items located in the battlefield, recording the position of each one inside the GIS. From these two datasets, collected items and explored terrain, new hypotheses can be put forward about the deployment of forces and the development of the engagement (Nolan, 2009).

In addition to geographical and archaeological data, other types of sources may be integrated into the system, since it is possible for ancient maps to be geo-referenced directly into the same environment (Knowles, 2008) and for textual information to be transformed into geographical events (unit deployments, changes in environment, known buildings, etc.).

As an example of the methodology we provide two illustrative images of how all the data generated by a battlefield survey can be integrated into a GIS. The data are derived from research carried out to interpret the battle of Talamanca (Catalonia, Spain), fought on 13 August 1714 (Rubio, 2008a). Fig. 1 shows the result of fieldwork, where the different lines represent the archaeologists' tracks and the points indicate the position of items collected in the battlefield. Fig. 2, on the other hand, is the hypothesis of deployment generated by the research team through the study of textual sources in conjunction with the survey results. Other examples of battlefields where bullet distribution maps were developed using similar methodologies are Edgehill, 1642 (Foard, 2005, p. 13); Naseby, 1645 (Foard, 1995, p. 249); Landskrona, 1677 (Knarrstrom, 2006, p. 72) and Culloden, 1746 (Pollard, 2009, coloured plate no. 13).

1.3. Issues and questions

Allowing for a few variations the method described is the standard way of working on a battlefield from an archaeological point of view. Apart from the choice of referencing system there are three different ways of establishing transects: intensive (transects are adjacent, in order to explore the entire battlefield), extensive (the archaeologists explore the battlefield leaving a fixed and regular distance between each parallel course) and organic (each team explores the terrain following every possible path). The latter strategy was the one chosen in Talamanca, as the roughness of terrains and the abundance of bushes and trees made it impossible to use the other — more desirable — strategies. At all events, although intensive surveys are undoubtedly the best option (as 100% of the battlefield is explored) the usual choice is the extensive

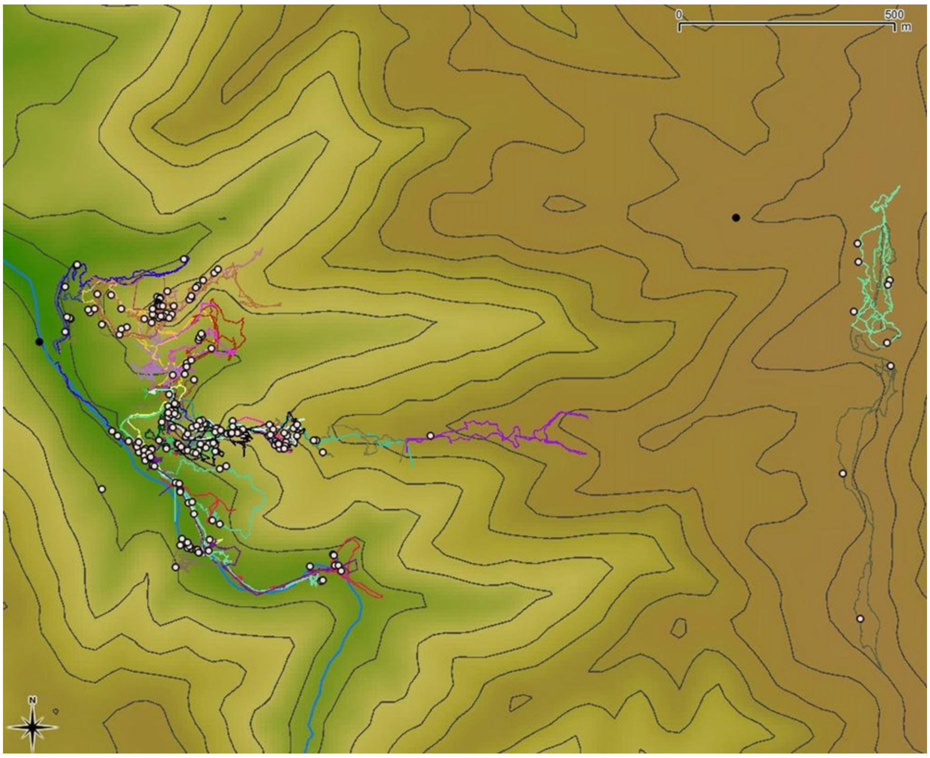

Fig. 1. Results of archaeological survey on the Talamanca battlefield.

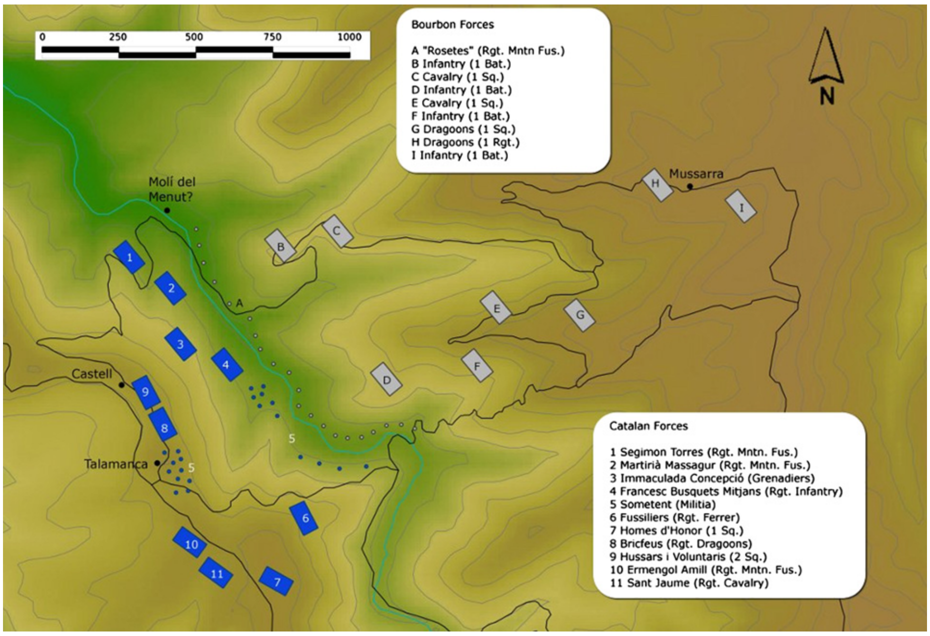

Fig. 2. Deployment hypothesis based on textual and archaeological sources.

strategy. The distance between tracks, as well as their direction, is established according to time requirements and the possibilities of each project.

The most important objectives of battlefield archaeology are to improve both the interpretation of the engagement and knowledge about the people involved in it, and this methodology has repeatedly proven its value by providing greater insights in this regard. Nevertheless, the battlefield archaeology community has acknowledged a number of problems and questions that arise from this work. Some of these will be discussed here in relation to eighteenth-century battlefields, as this is the period chosen to develop our proposal.

The main question is: can a battle really be interpreted on the basis of an archaeological survey? If we focus on the period spanning the sixteenth to the nineteenth century, and assume the task of detecting the battle lines formed by the different armies, according to the tactics they used, then we need to consider that this era is characterized by black powder ammunition used by massive formations of infantry and cavalry, fighting with muzzle-loaded firearms and edged steel weapons and supported by artillery batteries (for a general overview of these tactics and weapons, see Hughes, 1997). Thus, we would have to detect the number of soldiers that formed each line, in how many ranks they were deployed, and the orientation of these formations. Finally, in order to interpret the battle we would need to be able to detect firing ranges, as well as the advances, retreats and other dynamics of each battle line.

This is a daunting task. Furthermore, we also need to be aware that the data we collect during an archaeological survey is not the original record of the battle. Battlefields are affected over centuries by looters and chemical processes which degrade the quality and quantity of data, and the survey will not, therefore, be able to recover all the items dropped during the battle. This aspect must be taken into account in the final analysis of the material remains, and two further questions thus arise: Can useful information be obtained from an extremely degraded battlefield? How can fieldwork be planned to take into account these degradation processes?

To conclude these preliminary questions it is important to note that while the methodology is somewhat different from a standard archaeological field survey, the results of this work could be applied to such a survey. Indeed, although the collection of materials and the organization of transects is different, the core of the technique remains identical to standard surveys, including the spatial analysis of the results. Therefore, the method we propose can easily be applied to other situations, thereby extending the scope of this work beyond battlefield archaeology.

2. The model

In order to explore these issues we need a way of replicating both the type of archaeological data generated by a military engagement, and the different ways it can be collected. It would be complicated to plan such research using real fieldwork, as each battlefield is unique. Indeed, the usual reason for excavating a battlefield is to understand the events that took place there, thus making it difficult to compare different methods used in different battlefields. Moreover, we cannot work twice on the same area in order to test different strategies, as the results would be directly related to the order in which they were obtained.

At all events, the design of real experiments capable of understanding how weapons are fired and projectiles fall is extremely interesting, as it allows us to gain insight into depositional processes. Several studies have followed this direction, including work on artillery case shot (Allsop and Foard, 2007), mid-eighteenth-century flintlock muskets (Roberts et al., 2008) and seventeenth-century matchlock muskets (Miller, 2010). This research is extremely valuable in terms of understanding individual capabilities, although obviously we cannot emulate a military engagement with thousands of soldiers; neither can we fire a number of firearms equal to those used in a real battle, and hence real experiments cannot be used to understand global spatial patterns.

Here we propose the use of computer simulation to analyse these questions, as this would seem to be ideally suited to the battlefield scenario. The aim is to create models capable of exploring battlefield archaeology, using computers as virtual labs. Although this approach is new in terms of battlefield fieldwork it should be noted that methodological simulations are one of the most active branches of the application of computer simulation in archaeology (Costopoulos, 2010, p. 24). This technique, known as tactical simulation (Lake, 2001, p. 729), allows archaeologists to test different stages of their research, including fieldwork and laboratory analysis. It can also be used to simulate depositional processes (Lake, 2000), and even post-depositional events.

As our goal is to analyse different strategies of field surveys we will need to simulate at least two additional processes: the fall of battle-related objects, and the possible degradation of the site. We have therefore divided the experiments into three different steps (see Fig. 3):

1. **Generation of a battlefield**. We need to create battlefields that are realistic enough to emulate spatial patterns similar to those that can be found in reality. Here we decided to narrow the research to excavations of black powder battlefields, especially those associated with the prominence of linear tactics (eighteenth-century). As we want to analyse the distribution of musket balls we will simulate the behaviour of the individual soldiers who fired them.
2. **Degradation of the virtual archaeological record**. Archaeologists do not find the original record created by the battle, but rather a degraded version from which a substantial amount of material will have been removed. This is why we will generate different degraded battlefields, as we want to explore the impact of this factor on archaeological research.
3. **Simulation of fieldwork**. The final step is the recovery of battlefield items that will lead us to simulate an archaeological survey. During this phase we will test different fieldwork strategies in order to detect the most important variables and determine how they affect final interpretations.

These steps will be designed as different simulations. The requirements for choosing a particular simulation technique are listed below:

- Explicit spatial coordinates.
- Possibility of defining behaviour and the internal state of different entities (soldiers, archaeologists, musket balls).
- Heterogeneous parameters (different values for each soldier and even each musket ball).

Given that we want to define individual behaviour (phases 1 and 3) for different agents we will use agent-based simulations as the most efficient way to model and explore this concept. The technique is optimal for simulations with heterogeneous environments and entities modelled with different behaviours, and it has been widely used in archaeology since its beginnings (for details about the methodology, see Epstein and Axtell, 1996; Gilbert and Troitzsch, 2008; Gilbert, 2008. For its use in archaeology, see Doran et al., 1994; Doran, 1999; Lake, 2000; Diamond, 2002; Kohler and van der Leeuw, 2007; Costopoulos and Lake, 2010).

The software we will use to implement the model is the Pandora Library, created by the social simulation research group of the Barcelona Supercomputing Centre. This tool is designed to implement agent-based models and to execute them in high-performance computing environments (Rubio and Cela, 2010). It has been explicitly programmed to allow the execution of large-scale agent-based simulations, and it is capable of dealing with thousands of agents developing complex actions. The tool used has full GIS support to cope with simulations in which spatial coordinates are relevant, as in the case here, where we want to detect and compare spatial patterns. This library also allows the researcher to execute several simulations by modifying initial parameters, as well as to distribute particular executions with high computer costs by using a computer cluster. A cluster is formed by different linked computers (called nodes); the distribution divides the computing cost of the execution between different nodes, each of which executes a part of the entire simulation. As a result we will be able to run the simulation in a fraction of the time that would be needed if we were using a single computer.

The results of each simulation are stored in hierarchical data format (HDF), a popular format that can be loaded by most GIS. This feature is particularly useful, as we will also use GIS to analyse simulation results.

Finally, Pandora is complemented by Cassandra, a program developed to analyse the results generated by a simulation created with the library. Fig. 4 shows this application, illustrating the middle phase of our simulated battle.

The three simulations we have identified will generate approximately the same data we would gather in the excavation of a battlefield. In both cases (real and virtual excavations) the final and most important phase is the analysis of recoveries in order to detect spatial patterns that help us understand the battle. This final step will be done using Cassandra, GRASS and QGIS to execute the spatial analysis, and the R software package to calculate statistics.

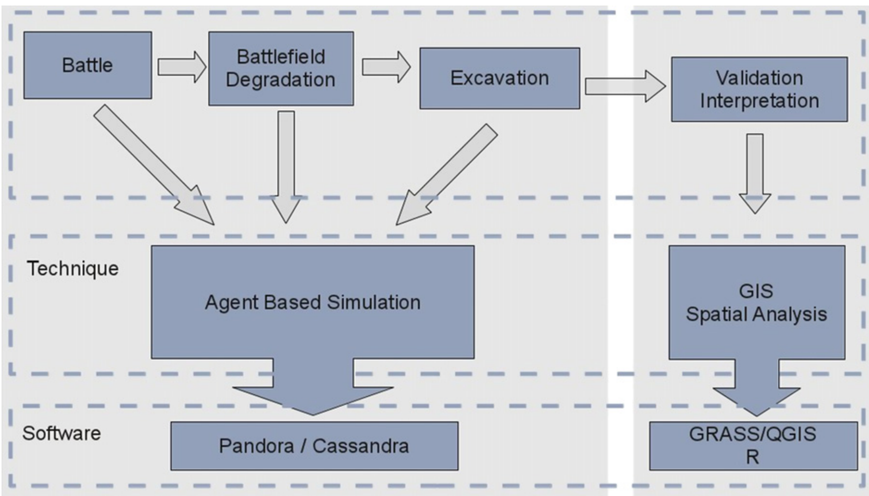

Fig. 3. Architecture of the simulation, detailing the different steps of the research and the chosen techniques and software.

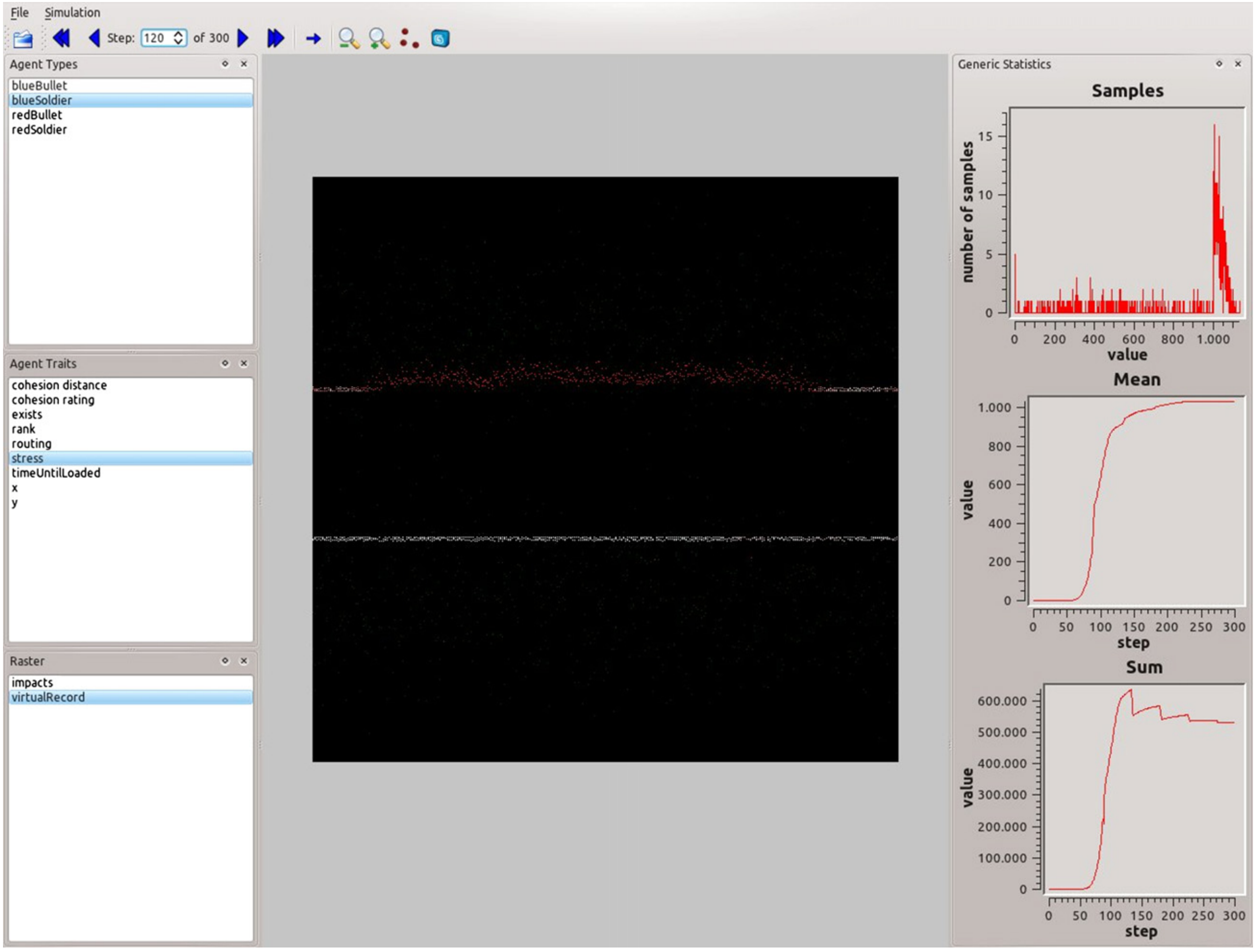

Fig. 4. Cassandra application, designed to explore statistical and spatial patterns of agent-based models.

2.1. Simulation of an eighteenth-century engagement

As already mentioned, the first step of research involves simulating and recording a battle. As we have to simulate the dynamics of eighteenth-century battle tactics our experiment will recreate two opposed infantry battle lines functioning under the tactical system known as linear warfare. The behaviour of soldiers will be defined at an individual level, as we are interested in tracking each musket ball fired by each soldier during the engagement. The emergent process should be similar to the type of battles described in primary accounts and drilling manuals, and the comparison of simulation results with this knowledge will tell us whether the scenario is realistic enough to be useful in practice.

The scale of this simulation must take into account that we want to track individual bullets (and as a consequence, soldiers). The space will be divided into regular square cells with sides of 0.5 m. A soldier occupies approximately this area within an infantry line, and we will track the number of musket balls fallen on each of these cells during the battle. The error introduced in terms of bullet location is not relevant, as handheld GPS devices used in fieldwork often have a wider margin of error (4–5 m). Since we want to analyse spatial patterns, an error of this magnitude will not significantly modify the interpretation.

Regarding temporal resolution, we have chosen a time step of 1 s, which means that each second we will be evaluating the internal state of soldiers and their actions. This temporal granularity will allow us to track reloading times, soldier movement and the firing of bullets.

Continuing the definition of our model, let us now focus on the battle environment (i.e. landscape). As our goal is to understand the dynamics of battle lines and the impact they have on the archaeological record, we will not, for the time being, deal with terrain effects. Mountains and hills, rivers, hedges, towns and several other geographical features are extremely important in determining the outcome of any battle, but at this stage of research we have decided to create homogeneous battlefields in order to focus our efforts on the interaction between two battle lines. This is an acceptable simplification, as in several primary sources there is no mention of the impact of terrain on a fire exchange between lines because the area was completely flat (see, for example, Rubio, 2008b, p. 121; Falkner, 2005, p. 183).

Regarding tactics, we want to execute simulations with a reasonable number of soldiers (replicating spatial patterns similar to a real battle), but limited enough to avoid further computing costs. We will therefore simulate the engagement of two battle lines, each deploying two infantry battalions (around a thousand soldiers). They will be formed in three different ranks, following standard tactic drills (Nosworthy, 1992; Hernàndez et al., 2010).

The soldier will be the atom of our simulation in terms of decision-making processes. It is important to note that at the start of the simulation both infantry lines will already be deployed and advancing against each other. For this reason we have avoided introducing the concepts of NCOs and officers. Although the definition of these types of agents would be essential if we wanted to explore real battle tactics, the fact that we are defining this model in order to understand the archaeological record enables us to focus our efforts on the behaviour of soldiers and the firing of projectiles, rather than on the line as an effective military unit. Thus, we have created a model built on psychological constraints, following the hypotheses proposed by authors such as John Keegan, Philip Sabin and Christopher Duffy (see Keegan, 1983; Sabin, 2000; Duffy, 1998). Each soldier has been modelled with variables such as position, reloading time and, especially, a level of battle stress that simulates his psychological condition. This stress is increased by different factors such as the number and proximity of enemy soldiers and friendly casualties, and is decreased by the particular cohesion rating of the soldier, the number of friends near him, etc. When this stress rises above a certain threshold the soldier routs and tries to run away from the enemy. As the routing of soldiers affects friendly soldiers, this simple behaviour creates the type of routing chain portrayed in different descriptions from this century, thereby breaking the battle line (see examples in Falkner, 2005).

To sum up the soldier model we have created, the variables that define the internal state of each agent are:

- Maximum stress: Maximum level of stress that a soldier will be able to endure. Once surpassed, the soldier will rout.
- Current stress: Level of stress of the soldier during this particular time step.
- Cohesion rating and distance: Following the theories of Marshall (Marshall, 2000) we have defined a cohesion parameter that minimizes the impact of battlefield stress on every soldier. Each individual will avoid the increase of stress thanks to the proximity of other friendly soldiers. This value depends on the cohesion distance (the maximum distance at which a soldier positively affects other ones) and the cohesion rating. This is a weighted factor defined by the experience and training of each soldier; the highest factors define elite units, while the lowest refer to militia and other untrained warriors.
- Current/reloading time: Time (in seconds) that a soldier needs to reload the weapon and fire again. It should be noted that in our model, reloading time will not be modified by the soldier's stress, as primary sources tend to show that soldiers fired as fast as they could once the engagement had started (Duffy, 1998, p. 210).
- Accuracy: As the quality of muskets was very poor in terms of accurate fire, we have established a probability of 10% of impact every time a musket ball crosses a cell containing a soldier, this being based on experimental findings (Roberts et al., 2008).

Finally, we will create and simulate musket balls fired by soldiers. We are interested in knowing where these bullets are falling, so each one of them will follow a realistic trajectory with the following variables:

- Initial velocity (V_0). We have established an initial velocity of musket balls within a normal distribution and a mean of 450 m/s, following previous documentary and experimental works (Roberts et al., 2008).
- Initial height (H_0). The height from which the musket is fired by the soldier. This has been defined according to a normal distribution with a mean of 1.5 m.

The range of the musket ball is a function of these two parameters, as the angle of firing will be defined as 0° in terms of simplicity. Therefore, every time step in which a soldier reaches his reloading time (45 s) he fires his musket in the direction of the enemy. The bullet begins travelling with speed V_0 and initial height H_0, which will decrease under the effect of gravity. As defined here, if the bullet crosses a cell in which a soldier is located a test is carried out to see whether there is an impact. In the event that a soldier is hit, both the agent and the bullet are removed from the simulation (as the soldier will be dead or wounded, but in any case unable to continue fighting). If there is no impact the musket ball follows its path until hitting the ground. At that point the simulation records the cell in which this object falls. It is important to note that bullets which hit soldiers are not recorded, as they probably did not fall to the ground.

Although it could be interesting to use more advanced ballistic models based on real experiments, at this stage of research we have not modelled effects such as 'bounce and roll' (the distance travelled by the musket ball after hitting the ground). Although these aspects can be relevant in terms of bullet distribution (Miller, 2010, p. 121) we would need to simulate different types of terrain to determine the real impact of 'bounce and roll'. Thus, the advanced ballistic model and the definition of different soils would bring a high level of complexity to our model, and at present there are no published experimental data about this effect in relation to eighteenth-century flintlock muskets. Another important factor, the angle of the musket at the moment of firing, is also omitted because it would introduce a high degree of uncertainty into the model, thereby complicating the interpretation of results.

As the aim of this paper is to define a general framework for experimenting with different survey strategies, we have tried to keep the battlefield simulation as simple as possible, defining only the most important processes that affect the generation, degradation and gathering of objects. Finally, even though we are not interested in developing a highly realistic individual simulation of the battle, the proposed model is generic enough to integrate such simulations into further research.

At the beginning of the simulation the two battle lines will already be deployed but not engaged; at this point there will be 200 m between them. In Each time step both formations will advance against the enemy (at a reasonable pace of 1 m per second), until they are 80 m apart, this having been established as a common firing distance (between 50 and 100 m; see Duffy, 1998, p. 208). At this point they stop moving and the soldiers begin to fire volleys against the enemy until they are wounded or routed.

The battle we will use as an input for posterior steps can be seen in Video 1. After 5 min of simulated time the battle line deployed in the upper side of the simulation has broken, and its soldiers are running away from the battlefield. It is important to note that this is a particular simulation of our model, and even though the level of non-determinism is high (due to several stochastic variables such as height, velocity and impacts, etc.) the general results between simulations are similar in terms of spatial structure.

Supplementary data related to this article can be found online at doi:10.1016/j.jas.2011.09.020.

The dynamics observed in the simulation seem correct in relation to the hypotheses proposed by the authors cited above. Once engaged, soldiers fire as quickly as they can while psychological stress grows gradually, until one of the lines hits a breaking point. At this moment the formation disintegrates, as every soldier is trying to run away from the enemy.

Although it is difficult to test the validity of the musket bullet distribution the model implements a simple yet reasonable physical model of ballistics, and the behaviour of soldiers is realistic enough. These points show that the matrix in which we have stored all the impacts of musket balls (a raster map, in GIS vocabulary) is a fair replica of the type of spatial distribution that can be found when excavating a real battlefield.

2.2. Degradation of the archaeological record

An additional process to be considered is the degradation of the battlefield. The raster map is a record of materials that could be found in the area the day after the engagement, but obviously many items could accumulate or be destroyed from this day until the one on which the archaeologists explore the battlefield. To reflect this problem the second step of our proposal involves the design of a simple simulation that will remove musket balls according to a random distribution. As different battlefields can have different levels of degradation we have created ten different results, with an increase in bullet removal of 10% (one of them will not have any musket ball removed, the second one 10%, the next one 20%, etc., up to 90%).

2.3. *Reproducing an archaeological survey*

The final phase we need to simulate is the archaeological fieldwork. This will be developed as a collection of surveys in which each virtual archaeological team will follow a straight transect through the entire battlefield, parallel to the other ones. The width of this transect has been set at 1.5 m (3 cells), as this is roughly the distance that a metal detector can cover. When a team passes through a cell with musket balls they collect all of them, and this number is recorded on a raster map in the exact location. There are several reasons why a real survey would not collect the entire set of musket balls from each cell (expertise in the use of metal detectors, depth of the musket ball, soil, etc.), but in terms of modelling this issue can be overlooked. A mechanism to limit the number of gathered bullets would generate an additional random variable (chance of detecting a musket ball), and the final effect would be identical to excavating a more degraded battlefield: we will get fewer musket balls but the general spatial structure will be the same.

This raster map is equivalent to the result of real fieldwork (specifically the GPS waypoints that mark the position of collected items), and combined with the record of explored space (the transects, equivalent to GPS tracks of archaeologists paths) it creates the data we need to interpret the battle.

As we want to determine the consequences of choosing particular fieldwork strategies we will execute several simulations in order to explore the parameter space defined by:

- Distance between transects. This is a critical factor, which is usually based on the size of the battlefield and the time available to do the fieldwork. We will set five different values: 1.5 m (intensive fieldwork that covers the entire battlefield), 5 m, 10 m, 15 m and 30 m.
- Direction of transects. We want to know whether there is a relationship between the direction of the battle and the direction in which the site should be explored. With this in mind two different possibilities have been chosen. The first (called parallel) will see the archaeological teams following the same direction as the soldiers (from top to bottom), while the second will be perpendicular, i.e. following the orientation of battle lines (from left to right).

We will simulate the entire set of combinations of these values for each degraded battlefield, which generates 100 executions (10 levels of degradation × 5 distances × 2 directions). Fig. 5 shows one of these, with parameters set at 30% degradation, a distance of 5 m and a parallel direction.

3. Results and validation

While the visualization of these results using Cassandra is in itself interesting, it does not provide us with the desired insight regarding real fieldwork. To this end we need to validate the results by designing an indicator that can compare the quality of the data

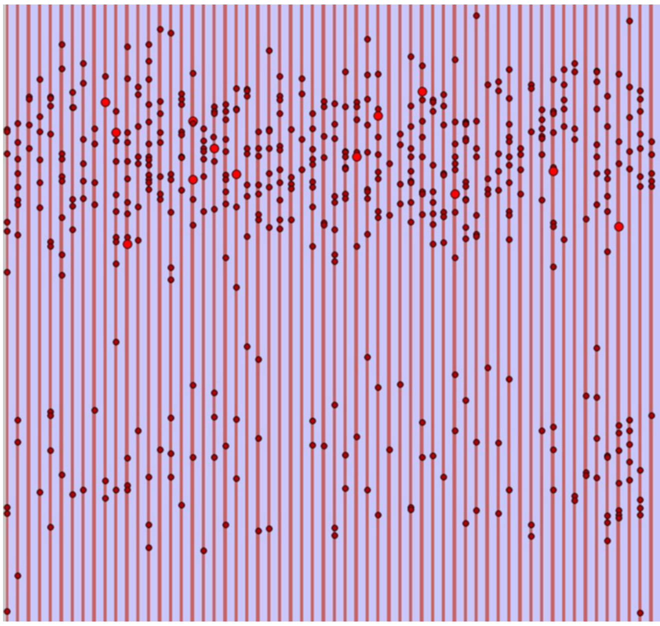

Fig. 5. Simulated excavation with 30% battlefield degradation, a distance of 5 m and parallel direction.

collected in different virtual surveys. Basic indices such as the percentage of items recovered are not good enough by themselves, as these values will not take into account the spatial integrity of data; situations can arise where we are collecting a high percentage of musket balls, but the global result has a different spatial distribution to that of the original record (i.e. when working only in a section of the battlefield).

3.1. *Survey Confidence Index*

Firstly, we are interested in capturing the general structure of the material distribution across the battlefield. Therefore, any calculation based on a comparative study of the location of individual bullets will be flawed, as we will only recover a small fraction of the total number of original bullets. The method we propose is based on the use of neighbourhood analysis. For each simulation we will create a new raster map with the original resolution of 0.5 m. The value of each cell inside these maps will be the maximum number of musket balls found in a cell located inside its neighbourhood (delimited by a window size of 4.5 m, or 9 cells). This means that each cell will mark the maximum values of musket balls that were recovered in its neighbourhood, rather than its original value. We have chosen to record the maximum value instead of other indices (i.e. mean, sum, etc.) because we are interested not in the total number of bullets that fell in the area, but rather in capturing the general trend in each particular area. The neighbourhood window is set at 4.5 m because this is the mean error of a handheld GPS device. As such we have adjusted the accuracy of the virtual archaeologists in the simulation to the accuracy of real fieldwork where these devices are used.

In the next step we calculate the root mean square error (RMSE) between the neighbourhood analysis of each simulation (called *simulatedN9*) and the one generated from the original record (called *baseN9*). RMSE is an estimator capable of measuring the difference between real calculations and those generated by the simulation of a given variable, and it is given by the formula:$\mathrm{RMSE} = \sqrt{\mathrm{MSE}(X)}$ where X is the analysed variable and MSE is mean square error:

$MSE = \text{mean}((X - X_s)^2)$ where X_s is the value resulting from the simulation.

The resulting index is an indicator about the loss of spatial information, and therefore it summarizes the two factors we want to analyse: number of bullets and structure of the distribution of musket balls. This preliminary Survey Confidence Index for a simulation with distance between transects *distX*, degradation percentage *degY* and direction *dirZ* is defined as:

$$SCI_{distX,degY,dirZ} = \sqrt{\text{mean}\left(\left(baseN9 - simulatedN9_{distX,degY,dirZ}\right)^2\right)}$$

Finally, in order to gain further insight we normalize and invert the index, assigning a value of 1 to the best simulated excavation and a value of 0 to the worst one. The result of this formula will be defined as the Normalized Survey Confidence Index:

$$NSCI_{distX,degY,dirZ} = 1 - \frac{SCI_{distX,degY,dirZ}}{\max(SCI)}$$

By examining the NSCI for each simulation we obtain a revealing preliminary result: the direction of archaeological work is relevant, as for each case the one with transects perpendicular to the line of advances/retreats provides better results than the other one. Moreover, the mean of these perpendicular surveys is slightly superior to that of the parallel surveys (0.15 vs. 0.13).

As stated at the beginning of this paper there is a logical interest in detecting which parameters are the most important when planning fieldwork. Fixing the direction as the best of the two (i.e. perpendicular), Fig. 6 shows the relationship between the other two parameters we have explored through the simulations: battlefield degradation and distance between transects. If we visualize these factors in relation to the NSCI we will easily detect different patterns. While the distance between transects affects the NSCI with exponential decay, the battlefield degradation has a linear impact on its value. This result is extremely interesting as it shows that it is far more important to choose a correct survey distance than it is to focus on the effects of degradation. Moreover, it seems that even in cases where actual battlefields contain only a small percentage of original fired ammunition, the interpretation is still possible in terms of coherent spatial structure.

It is important to consider that the usefulness of this indicator is not limited to battlefield archaeology. As noted above, the methodology of fieldwork is broadly common to other types of surveys, and therefore it could also be used to analyse them with comparable results. Even if the choice of variables to explore is different, this index would equally serve to compare the result of different survey strategies, both in battlefield studies and other archaeological projects.

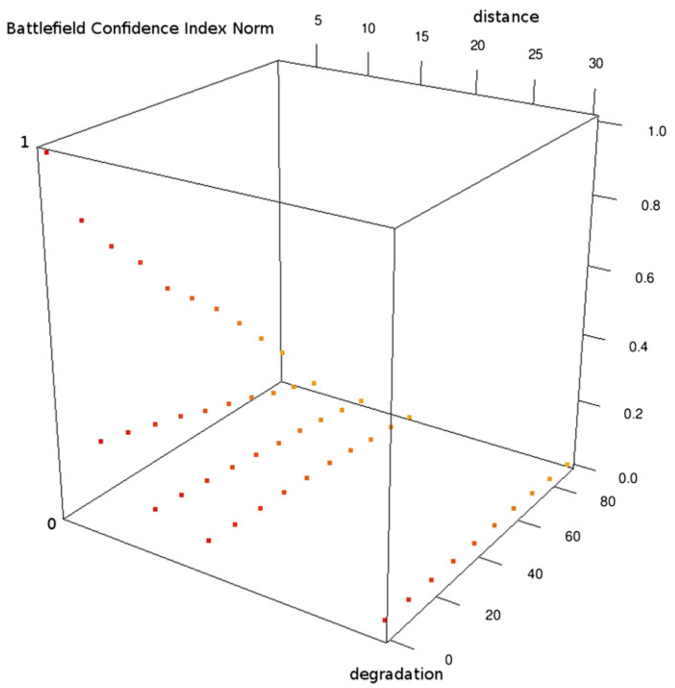

Fig. 6. Relationship between NSCI, distance between transects and battlefield degradation.

3.2. Battlefield profile

These simulation results can be used to explore the issue of the interpretation of highly degraded battlefields. In order to validate whether they can be studied we will create an additional spatial structure designed to contain information about the combat. We will fold the two-dimensional space of the battlefield (the raster map where recovered musket balls were recorded) into the axis of advances and retreats (our direction we have defined as parallel). The reason for this is that the other axis is extremely homogeneous from a spatial point of view, and it does not provide additional information about the dynamics observed during the simulation. Giving this new structure the same axis as the parallel direction, the value on each coordinate will be equal to the sum of existing bullets in the row corresponding to the other axis (see Fig. 7).

The structure, defined as a theoretical 'battlefield profile', allows us to compare recovered data with the original record. Fig. 8 shows the difference between the original battlefield and the recoveries provided by a virtual excavation with 70% degradation of the battlefield, a perpendicular direction and a distance of 5 m. It is important to note that the NSCI is rather low (0.08, the 40th index inside the rank of simulations) and that the percentage of bullets is only 5% of total musket balls. As can be seen in the figure, and contrary to expected results, the battlefield profile is extremely similar to the one provided by the original record. Both of them could be used to calculate firing distances between battle lines and their position, and also show that the line on the left-hand side of this profile was the one defeated, as the other side was capable of firing more bullets (having a wider dispersion than the other peak).

One of the aims of battlefield archaeology is to create a story about what happened during these particular events, a story capable of portraying not only how the battle developed but also of re-reading primary textual sources in the light of materials recovered from the battlefield. While the NSCI can help us to choose the best fieldwork strategies the battlefield profile should prove to be a useful tool in terms of improving the interpretation of a battle.

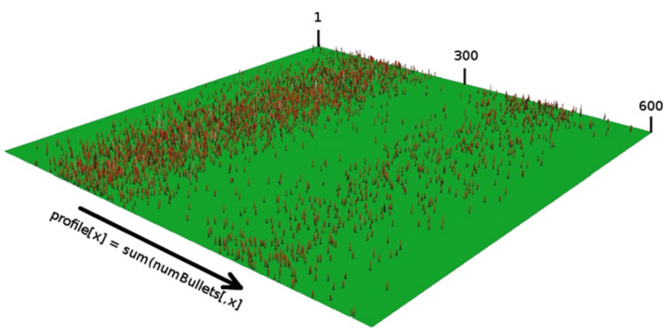

Fig. 7. Explanation of the spatial structure known as 'battlefield profile'.

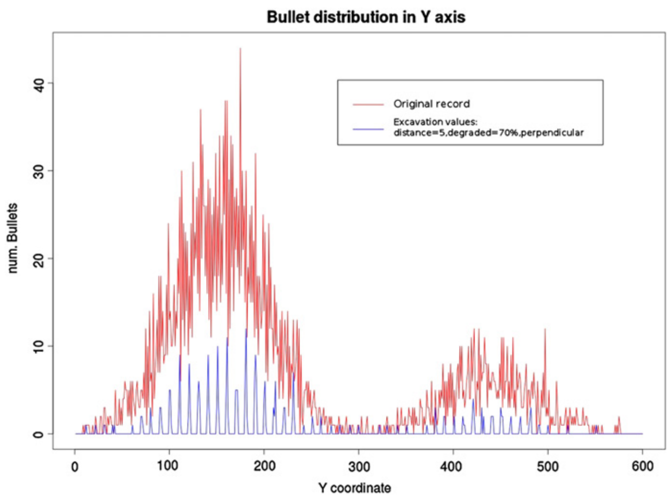

Fig. 8. Comparison of the battlefield profiles calculated from the original distribution and items collected during excavation.

This is because we will be able to define the axes that marked a military engagement if we are able to find these spatial structures through analysing the materials generated by them.

4. Discussion

This model has enabled us to explore some of the particular issues that characterize battlefield archaeology, and on the basis of the simulation results a number of recommendations can be made about fieldwork.

Firstly, when planning archaeological surveys, attempts should be made to organize the teams in perpendicular transects to the axis of advances and retreats (thereby following the lines along which the armies were deployed). Although this can be difficult at times (due to lack of information or rough terrain) it would be possible for most engagements, as the researchers usually have descriptions of the battle provided by primary textual sources. This approach can increase the number of recovered bullets by almost 30%, and as we have shown with the construction of our NSCI it is also better in terms of maintaining the spatial structure of the dispersion of bullets.

The second point will seem quite logical, although it is a common mistake made by most interpretations (including our own results, see Hernàndez and Rubio, 2010). The areas where fieldwork finds a higher density of bullets are not the zones where battle lines fought. This is because recovered musket balls are the ones that fell to earth because they passed by the targets at which they were fired. Therefore, it is necessary to establish the main areas of engagement by calculating the positions from where these bullets could have been fired. This approach will inevitably add uncertainty, as hypotheses would have to specify the areas in which firing was more probable from a statistical point of view (rather than showing only a single zone). On the other hand, it would provide a more correct and accurate depiction of the battle.

As regards the methodology itself has been shown to be an excellent way of understanding a battle, as even in cases with highly degraded battlefields we can gain insight into the engagement. Spatial analysis and statistics can be used to detect firing distances, the direction of combats, and to address the other questions noted at the beginning of this paper.

With respect to the battlefield profile it should be remembered that this spatial structure, although extremely promising as a tool to understand dynamics, has not been calculated from real events. Further research is therefore required to determine whether this distribution can be detected in recoveries using proper fieldwork strategies and spatial analysis.

It should also be noted that the work described here is a first stage in the design of more complex models. The most promising research line is focused on the development of advanced battle dynamics, in which context the introduction of hierarchies (officers and NCOs), the design of realistic terrains and the development of elaborated ballistic models are three of the most interesting avenues to be explored. At all events the model presented here can easily integrate the data generated by primary sources, GIS, drill manuals and real experiments. The results thus obtained would be extremely interesting for both battlefield archaeologists and military historians in terms of exploring differences between formations and firing tactics, the impact of quality amongst troops, etc.

A further point is that the post-depositional process simulated in this work is extremely simple, and was justified by the lack of research on these types of events (at least in terms of battlefield archaeology). Further research could therefore improve the model, including in relation to particular case studies that seek to emulate real events (i.e. action of looters, destruction of a section of the site, etc.).

Finally, it could be interesting to use this model to test other survey-related topics such as the use of transects with different orientations, or the impact of diverse metal-detecting skills among archaeological teams.

5. Concluding remarks

Although the use of simulation tools to understand past events is not a new approach it has not previously been applied to battlefield archaeology. The present paper shows that it is a promising approach which allows the researcher to integrate information from both textual and archaeological sources into a single experiment. Agent-based models would seem to be a particularly interesting technique, as they have enabled us to create fairly realistic battlefield dynamics at an individual level, replicating general events explained by primary textual sources as emergent processes. The fact that this individual behaviour can be located within spatial coordinates is what enables us to use archaeological data to validate our hypotheses, and to formulate new ones by combining these two disciplines (history and archaeology). The most important drawback of agent-based modelling is its high cost in terms of computational calculations. The development of tools like Pandora and Cassandra, which are capable of spreading this cost across different computers, is therefore important as regards advances in this research line, which remains at an early stage of development. At all events, the simulated experiments designed here to analyse fieldwork in battlefields provide an initial illustration of how the approach can be applied to the benefit of methods and techniques that are widely used in archaeology.

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