Journal of Visualized Experiments

HoneyComb – An Experiment Paradigm for Research on Human Collective Behaviour
--Manuscript Draft--

1 **TITLE:**
2 **The HoneyComb Paradigm for Research on Collective Human Behavior**
3

4 **AUTHORS AND AFFILIATIONS:**
5 Margarete Boos[1], Johannes Pritz[2], Michael Belz[3]
6
7 [1]Institute for Psychology, University of Goettingen, Goettingen, Germany
8 [2]Courant Research Centre Evolution of Social Behavior, University of Goettingen, Goettingen,
9 Germany
10 [3]Department of Psychiatry and Psychotherapy, University Medical Centre Goettingen,
11 Goettingen, Germany
12
13 **Corresponding Author:**
14 Margarete Boos
15 mboos@uni-goettingen.de
16
17 **Email Addresses of Co-authors:**
18 Johannes Pritz   (jpritz@gwdg.de)
19 Michael Belz   (mbelz1@gwdg.de)
20

21 **KEYWORDS:**
22 Collective behavior, behavioral rules, group movement, multi-client game, group coordination,
23 leadership, self-organizing systems
24

25 **SUMMARY:**
26 Here, we present the computer-based, multi-agent game HoneyComb, which enables
27 experimental investigations of collective human movement behavior *via* black-dot-avatars on a
28 virtual 2D hexagonal playfield. Different experimental conditions, like variable incentives on goal
29 fields or vision radius, can be set, and their effects on human movement behavior can be
30 investigated.
31

32 **ABSTRACT:**
33 Collective human behavior such as group movement frequently shows surprising patterns and
34 regularities, such as the emergence of leadership. Recent literature has revealed that these
35 patterns, often visible at the global level of the group, are based on self-organized, individual
36 behaviors that follow several simple local parameters. Understanding the dynamics of human
37 collective behavior can help to improve coordination and leadership in group and crowd
38 scenarios, such as identifying the ideal placement and number of emergency exits in buildings.
39

40 In this article, we present the experimental paradigm HoneyComb, which can be used to
41 systematically investigate conditions and effects of human collective behavior. This paradigm
42 uses a computer-based multi-user platform, providing a setting that can be shaped and adapted
43 to various types of research questions. Situational conditions (*e.g.,* cost-benefit ratios for specific
44 behavior, monetary incentives and resources, various degrees of uncertainty) can be set by

45   experimenters, depending on the research question. Each participant's motions are recorded by
46   the server as hexagonal coordinates with timestamps at an accuracy of 50 ms and with individual
47   IDs. Thus, a metric can be defined on the playfield, and movement parameters (*e.g.,* distances,
48   velocity, clustering, *etc.*) of participants can be measured over time. Movement data can in turn
49   be combined with non-computerized data from questionnaires garnered within the same
50   experiment setup.
51
52   The HoneyComb paradigm is paving the way for new types of human movement experiments.
53   We demonstrate here that these experiments can render results with sufficient internal validity
54   to meaningfully deepen our understanding of human collective behavior.
55
56   **INTRODUCTION:**
57   The computer-based multi-agent game HoneyComb[1] offers a methodological paradigm to
58   experimentally investigate how collective human movement patterns and group structures
59   emerge from individual behavior. Human participants are visually represented as avatars (black
60   dots) on a hexagonal virtual playfield resembling a honeycomb (**Figure 1**). Participants move their
61   avatars *via* mouse-click to reach goal hexagons, spend move resources (**Video 1**), and maximize
62   their monetary rewards by building cohesive groups (**Video 2**). Spatial conditions (*e.g.,* vision
63   radius), reward structures (*e.g.,* monetary goal fields), and communication channels can be
64   manipulated in order to discover which and to what extent these condition rules impact
65   coordination and leadership in collective movement.
66
67   The game's procedural/condition rules, goals, and reward motivators have been designed by
68   social psychologists to investigate human collective movement. In animal swarms as well as
69   human crowds, one can observe emergent phenomena (*i.e.,* global patterns) transpiring from
70   individual behavior that follows local rules. For example, schools of fish and flocks of birds seem
71   to move as coherent entities towards a spatial goal[2-4], despite large group sizes that reduce their
72   capacity for global or inter-individual communication. Empirical research[5-7], behavioral
73   modeling[8-10], and computer simulations[11-13] have shown that in diverse species, including
74   humans[14-16], complex patterns at the group level emerge without internal control or external
75   supervision. Local individual movement and, often times, simple rules on the microscopic level
76   are sufficient to generate orderly movement on the macroscopic level. Such experiments
77   contribute to increasing evidence[2,6] that not only large swarms but also small groups (human
78   groups as well as other animal groups) are coordinated by local interaction rules[1].
79
80   Our novel approach using computer-based multi-user avatar games shows one main advantage
81   in researching dynamic human collective phenomena. Using the HoneyComb avatar platform[1,17-19], spatio-temporal data of individual movement behavior (movement governed by actual
82
83   individuals) can be fully collected by the server, and the development of behavioral patterns and
84   collective structures can be analyzed with an accuracy of 50 ms (**Table 1**). As visual and auditory
85   sensory communication can be restricted by requiring participants to use earplugs and encasing
86   their workstations with partition walls, swarm and other crowd behavior conditions can be
87   approximated experimentally. In several experiments[1,17-19], we manipulated vision radius (global
88   *vs.* local, **Figure 2**), monetary incentives (**Figure 3a,b**), subgroups (**Figure 4**), and the co-presence

89   of other players (**Figure 5**) in order to test the impact of these variables on the emergence of
90   collective behavioral patterns such as human flocking behavior[17], leadership[1], and competition[18].
91   To collect the data, a setup of ten to twelve notebooks and one server was used (**Figure 6**).
92

93   The self-organized coordination of individual activities in group-living species has attracted much
94   scientific attention, particularly within the last decade. Examinations are wide-ranging, from
95   simple trail formation and path selection in ants to the complex emergence of vortex structures
96   in fish shoals, and even the segregation of bidirectional flows of pedestrians[2].
97

98   With our HoneyComb paradigm, we contribute a methodological approach to empirically
99   investigate the impact of varied situational options/constraints, diverse behavioral rules, and
100   individual characteristics on the microscopic level on the emergence of macroscopic behavioral
101   structures in humans. An important advantage is that the paradigm offers strictly controllable
102   experimental settings defined by experimenters, making it possible for manipulation to measure
103   the outcomes of a single experiment or compare multiple experiments. The virtual playfield can
104   be configured according to the requirements of the study design, and sensory communication
105   channels between the participants can be eliminated or reduced according to the experiment
106   parameters. Additionally, environmental affordances can be shaped (*e.g.,* competitive, non-
107   competitive consensus, and rescue settings). Thus, our platform enforces internal validity (*i.e.,*
108   matching the study design as closely as possible to the research questions) by offering the
109   possibility to manipulate/control variables relevant for the specific research question, using
110   human-governed movement data to examine human movement. Field experiments render
111   benefits in terms of external validity (generalizability) of results[15,20,21] to the real world, because
112   they do not preclude effects of unknown uncontrollable/insuppressible social cues as well as non-
113   and para-verbal behaviors in humans[1].
114

115   The computer-based multi-agent game HoneyComb has served to investigate the emergence of
116   coordination and leadership patterns of human players moving their avatars on the virtual
117   playfield. Participants were only provided local information about monetary incentives
118   obtainable on goal hexagons, which included the incentive for group cohesion based on the
119   multiplication of monetary rewards by the number of co-players who also ended up on the same
120   goal hexagon. In our first series of studies, we restricted the experiment setup to two simple
121   parameters of swarming behavior (alignment and cohesion) and reduced mutual information
122   transfer to "reading/transmitting" of only movement behavior of the other participants. We then
123   varied the sight radius of other participant movement behavior to either a global or local view of
124   the virtual playfield, which consists of 97 smaller hexagons, and limited the expendable
125   movement resources (possible moves) of the players.
126

127   The shape and the elements of the virtual platform and the experimenter-defined parameters of
128   games able to be played on said platform can be designed according to the specific research
129   questions. Depending on the research goal, the size of the playfield can be changed; the colors,
130   shapes, and meanings of the avatars can be adapted; resources can be implemented; and the
131   reward structure and content can be varied. More or less information, uncertainty, and
132   conflicting preferences can also be implemented[22]. Varying global player-view information and

control are also possible. Therefore, *via* experimental instructions, the environmental affordances of the experiment can be altered (*e.g.,* a consensus *vs.* escape scenario). In the next section, we will clarify how these variables can be applied by describing a real study that used some of these parameters to answer specific study questions.

PROTOCOL:

Data collection and data analysis in this project have been approved by the Ethics Committee of the Georg-Elias-Müller Institute for Psychology of the University of Göttingen (proposal 039/2012).

1. Experimental Setup

1.1. Choose a location that is away from a high-traffic area, such as in a computer lab or other specified area with individual workstations that can be configured as an LAN (local area network).

1.2. Arrange for 10 to 12 notebooks of the same type to be used for the experiment as well as one computer to function as the server (**Figure 6**). The server program as well as client programs need a JAVA runtime environment, which is available on all common operation systems (a Raspberry Pi as client can suffice).

1.3. Equipment configuration

1.3.1. Arrange notebooks on individual workstation tables with chairs as shown in **Figure 7**.

1.3.2. Connect notebooks to the server computer *via* Ethernet cables and a network switch to create a local area network.

1.3.3. Install partition walls between individual workstations to prevent visual sensory communication (eye contact, hand gestures, facial expressions, *etc.*) between neighboring participants.

1.3.4. Acquire earplugs (for one-time use) to be distributed to all participants to prevent audible communication between participants.

2. Participant Recruitment

2.1. Choose a recruiting location where there are a large amount of people, such as the entrance hall of an auditorium.

2.2. Address potential recruits using the standardized text that explains the purpose and background of experiment, experiment duration, maximum payment calculated according to performance, and requirement for participation in a multiplayer game on institution-owned laptops.

177

178 2.3. Ensure that participants can understand the English and German instructions and
179 questionnaires related to the experiments.

180

181 2.4. If the experimental design includes the use of colors, ensure that participants are free of any
182 color blindness that may prevent them from differentiating the colors used.

183

184 2.5. Do not recruit previous participants, as participants should be naïve to the experiment.

185

186 2.6. Lead willing recruits to a waiting area away from the recruiting area. Kindly request that they
187 await completion of the group recruitment without talking to each other. Explain that this
188 restriction is related to integrity of the experimental results.

189

190 2.7. Once 10 to 12 participants have been recruited, lead them into the pre-arranged computer
191 lab or specified area where the experiment will take place.

192

193 2.8. Before participants take their places in the partition-encased workstations, have the
194 participants sign a form designating informed consent.

195

196 2.9. Distribute the hygienic, one-time use earplugs to all participants. Inform them that audio-
197 visual communication with other participants is prohibited. Therefore, the use of earplugs and
198 partition-encased workstations is mandatory.

199

200 2.10. Have participants take their places in the partition-encased workstations.

201

202 **3. Experimental Procedure**

203

204 NOTE: In this experimental procedure, the game used by Boos *et al.*[1] is described as an
205 application example.

206

207 3.1. Preparation phase

208

209 3.1.1. The program itself is formatted as a zip-file HC.zip containing 1) the runnables HC.jar, 2)
210 three files for configuration, namely hc_server.config, hc_panel.config, and hc_client.config, and
211 3) two subfolders named intro and rawdata.

212

213 3.1.2. Create a shared folder on the server computer and unzip the HC.zip into this folder.

214

215 3.1.3. On each client computer, mount and access this shared folder and open a terminal (Linux,
216 Mac OS X: spotlight | search | terminal) or a prompt (Windows: search "cmd"), respectively. Use
217 the command "dir" or "ls" so that the unzipped files appear on each terminal.

218

219 3.1.4. Execute the command "java -version" on each terminal to ensure that a java runtime
220 environment is available. If not, install java before continuing.

222 3.1.5. Look in the three configure files.

224 3.1.5.1. Edit hc_server.configure to configure the 1) number of players, 2) minimum numbers
225 and maximum numbers of moves each player can make, 3) values of the so-called nuggets, and
226 4) perception radius condition (local or global).

228 NOTE: The two perception conditions are the global condition (player can see positions of avatars
229 of all participants) and local condition (player can see only those avatars adjacent to their avatar;
230 see **Figure 3**)

232 3.1.5.2. Edit hc_client.configure to tell the clients the server's IP.

234 3.1.5.3. In hc_panel.config, adjust the size of the hexagons according to the screen's resolution.

236 3.1.6. First, start the server program HC_Gui.jar (**Figure 8**) using the command "java -jar
237 HC_Gui.jar". Then, start the client programs on each workstation using the command "java -jar
238 HC_ClientAppl.jar".

240 NOTE: The clients' screens should display the message, "Please wait. The computer is connecting
241 to the server." In the server GUI, a line appears displaying the IP address of each of the clients.
242 When all clients are connected, the server program displays the message, "All Clients are
243 connected. Ready to start?"

245 NOTE: The experimenter can prepare the session up to this point.

247 3.1.7. When all participants have taken their places, give the final instructions before they insert
248 the earplugs.

250 3.1.8. Click "OK" to start the session. Hereon, the experiment is controlled only by the
251 instructions on the screens visible to participants. Instructions for a single experiment require
252 multiple screen pages, and reading is made possible by the participants paging back and forth as
253 necessary.

255 NOTE: Each participant indicates, by clicking a designated button on the screen, that he/she has
256 read the instructions. The experiment cannot commence until all participants are finished
257 reading the instructions.

259 3.2. Testing phase
260

3.2.1. Observe whether the participants are mouse-controlling their avatar dot (twice as big as the visible avatar dots of the other participants) on the HoneyComb virtual 97-hexagon playfield (see **Figure 1**).

3.2.2. Have participants start the testing phase in the center of the field, then move on the HoneyComb virtual playfield according to the previously provided instructions on screen.

3.2.2.1. All instructions on how to play the game are placed as editable html-files within the program folder of the HoneyComb game. See subfolders intro/de and intro/en for German and English instructions, respectively.

3.2.2.2. Have players left-click into the adjacent small hexagon of their choice to move their avatar dot. Only adjacent fields can be chosen for the initial and subsequent moves.

NOTE: After each move, a small tail appears for 4000 ms for each participant, indicating the last direction from which he/she hailed.

3.2.3. Allow each participant to partake only once in order to avoid possible biases.

NOTE: The game described here requires 5-10 min, including the reading of instructions. Overall, 400 participants in 40 ten-person groups were tested by Boos et al.[1].

3.2.4. Do not restart the experiment with the same participants if there is a technical breakdown or if a participant fails.

4. Post-Test Phase

4.1. Once the game is completed, have participants fill out questionnaires assessing demographic data, Big Five personality factors, perceived levels of stress or calmness, and pay satisfaction (to be paid upon completion of the experiment). These questionnaires can be offered as stand-alone html-files.

4.2. While participants fill out questionnaires, prepare anonymous envelopes with the appropriate amount of money earned in the HoneyComb game just completed. The game's HoneyComb-computed amounts to be paid to each player are stipulated on the server screen.

4.3. Distribute the earned payments to participants as they exit the testing area.

4.4. Close the server program, then close the client programs once the server program has finished closing.

4.5. Transfer the data, in the form of 2 text files marked by day- and time-stamp of the experiment, to a USB stick.

REPRESENTATIVE RESULTS:

An initial experiment with the HoneyComb paradigm demonstrated that humans showed basic signs of flocking behavior, such as seeking the proximity of others, without being rewarded[17]. Subsequently, we addressed the question of how individual humans can be behaviorally coordinated to reach the same physical target/goal also investigated by Boos *et al.*[1], focusing not only on unspecific flocking behavior, but also group coordination and leadership behavior. Using the above-described experiment-defined parameters, goal hexagon locations were defined, and a monetary reward option was used to examine shared goals based on shared incentives, as well as motivation toward group cohesion. Motivation to achieve group cohesion was enhanced by stipulating an additional reward based on how many other participants ended up in the same goal hexagon. Within each of the 40 ten-person groups, two subgroups (a minority group comprised of two randomly selected individuals and a majority group comprised of the remaining eight) were created by giving the following levels of information. The two minority group members were informed about the location of one two-euro prize hexagon and five one-euro prize hexagons (**Figure 9,** left). The eight members of the majority group were not informed about the two-euro prize hexagon and instead were shown the locations of six equally rewarded one-euro goal hexagons (**Figure 9,** right). None of the participants were told that there were different subgroups.

We designed our study questions according to Couzin *et al.*'s[23] computer simulation model. Because the only information exchanged among the players were their abilities to perceive the movement of other players, we aimed to see (i) if this information was sufficient for the informed/higher rewarded minority group to coordinate the movements of the uninformed/lower rewarded majority group, and if so, (ii) how the double prize goal-informed minority group would/could lead the uninformed majority to their two-euro goal hexagon. As stated earlier, we restricted these study designs to two basic parameters of swarming behavior, 1) alignment (group members moving towards a goal hexagon) and 2) cohesion (group members tending toward moving as group). For the alignment parameter, we set up the six goal hexagons that granted a monetary payoff. For the cohesion parameter (*i.e.,* making move choices that were coordinated with moves with fellow participants), we granted participants a reward based on the amount of avatars at the end that were in the same hexagon as their own.

The HoneyComb playfield contains 97 hexagons. All participants' avatars began the game together in the honeycomb's middle hexagon. Each player was granted a maximum 15 move-count. All were restricted to move their avatar (*via* a mouse click) only across one of hexagon's six sides to an adjacent hexagon. The game ended when every avatar was on a payoff field or when every player had completely used their 15 move-count.

An additional experiment factor was implemented to answer a third study question: (iii) whether perception radius (global *vs.* local condition) of the other participants affects movement coordination. The perception of half of the 40 ten-person groups was restricted on a random basis, which meant that twenty groups (local condition) could perceive the movement of only those avatars adjacent to their avatar. The remaining twenty 10-person groups (global condition) could perceive all participants' avatar locations and movements.

349

350 To answer question (ii) [which movement characteristics of the minority groups led to more
351 success (successfully reaching a goal field as a group and therefore greater monetary reward)],
352 we defined and analyzed various movement behaviors including first mover, shared movement
353 paths/directions of the two minority participants, path lengths, average time between moves,
354 initial-move order among participants, Big Five personality characteristics (extraversion,
355 openness, *etc.*), and computer literacy. The statistical procedure, a finite mixture model with two
356 binomials, and detailed results are published in Boos *et al.*[1].

357

358 Our study demonstrated that in a group of humans, assigned avatars in a 2D HoneyComb play
359 field (moving according to the above-described parameters and conditions), 20% of them (the 2-
360 person minority group) based solely on their movements could successfully lead the other 80%,
361 even when their perception was restricted to only adjacent avatars on the playfield. Here,
362 successful leadership of these 2-person minority group participants entailed that their fellow
363 participants made similar initial moves and that these 2-person minority participants were first
364 to make an initial move[1] (**Video 2**). We also found, surprisingly, that neither personality variables
365 nor computer literacy among these minority participants played a crucial role in their success.

366

367 **FIGURE LEGENDS:**
368 **Figure 1: Playfield of the computer-based multi-agent game HoneyComb.** Visual representation
369 of human players as avatars (black dots) on a hexagon virtual playfield.

370

371 **Figure 2: Local *vs.* global perspectives.** Participants with local perspectives can only see other
372 players' avatars within their visual range. In this case, the marked player (red) is only able to see
373 4 out of 9 co-players. A global perspective, if configured, would provide visibility of all co-players.

374

375 **Figure 3: Monetary incentives.** This illustration shows how monetary incentives can be
376 implemented within the HoneyComb game. Avatars marked as grey are outside of the local
377 perception radius and are thus invisible to the respective player. Two different points of view are
378 shown. (a) Informed player: this player is endowed with one higher-rewarded goal field, which is
379 marked as "€€", (b) uninformed player: this player is provided six equally lower-rewarded goal
380 fields, which are marked as "€".

381

382 **Figure 4: Subgroup avatar experiment.** In this scenario, two sub-groups are created by coloring
383 the participants' avatars as blue and yellow.

384

385 **Figure 5: Single *vs.* joint game.** This illustration shows two different settings from one player's
386 point of view, comparable to Belz *et al.*[17] (1a/b) Single game: co-players are invisible and cannot
387 be found on the hexagon virtual playfield, (2a/b) joint game: co-players are visible as long as they
388 stay within the local perception radius of other players.

389

390 **Figure 6: Server and client configuration.** Ten to twelve notebooks (clients C^1 through C^{12}) should
391 be arranged in the vicinity of (and connected to) the server computer. The use of partitions
392 encasing each participant's workstation (indicated as thick lines) prohibits visual communication

393   with others outside the virtual environment. Use of LAN-cables instead of WLAN is recommended
394   due to less latency and more reliable data throughput.
395
396   **Figure 7: Contextual setting.** Communication (sensory, visual, auditory) among participants is
397   restricted due to the use of partition walls and earplugs.
398
399   **Figure 8: Graphic interface on the server.** For each connected client, there is a line showing IP
400   and other data (*e.g.,* number of moves, position, amount to be paid to each player).
401
402   **Figure 9: Successful leadership.** On the left side, the screenshot shows one informed player
403   approaching a monetary goal field (see also **Figure 4**), successfully leading five other players to
404   his/her goal field. On the right side, an uninformed player lost sight of his/her co-players.
405
406   **Video 1: Example of collective movement from the perspective of an uninformed player.**
407
408   **Video 2: Example of collective movement from the perspectives of the two informed players**
409   **in the same game as Video 1.**
410
411   **Table 1**: **Data format.** Each participant's moves and associated timestamps on the hexagon
412   virtual playfield are recorded as hexagonal coordinates in separate rows, enabling the use of
413   hierarchical/mixed modelling. The table shows an excerpt of the dataset generated by a group
414   consisting of 10 players.
415
416   **DISCUSSION:**
417   One fundamental question in using multi-client virtual environments as a research paradigm to
418   investigate human collective behavior is whether the results are applicable to actual scenarios.
419   In other words, does the methodological approach yield results with sufficient ecological or
420   external validity? Representing human participants as avatars on a virtual playfield and letting
421   them move *via* mouse-clicks reduces social cues. Additionally, keeping communication to a
422   minimum allows experimenters to investigate which tacit behavioral cues are transmitted among
423   humans that may affect human group coordination and leadership behavior and under which
424   environmental affordance (*e.g.,* rescue, competition, evacuation) these behaviors are affected
425   by more and to what extent. As long as there is strict adherence to the two pre-testing phases in
426   the protocol and testing procedures, this reductionist approach guarantees internal validity. In
427   order to allow the transfer of results to "real" group and crowd dynamics, the experimental setup
428   and test phases may be gradually modified to become more complex (*e.g.,* allowing for additional
429   communication beyond mere transmitting/reading movement behavior, adding information on
430   individual characteristics embedded semantically into various real-world scenarios, *etc.)* and
431   described in the on-screen instructions read by the participants before the game starts.
432
433   To address the matter of external validity, the hexagon playfield [initially chosen to standardize
434   player's movements to standardized, two-dimensional hexagonal coordinates due to (pre-tested)
435   usability and reduction of confounding factors] can be varied. A two-dimensional grid with free
436   movement choice would enable players to create more continuous and complex movement data.

A three-dimensional environment created by Unity- or Unreal-Engine, for example, can also heighten the ecological/external validity. However, with each step towards lessoning the restriction of movement, a problem arises. With rising complexity of freedom-of-movement in the simulated scenario, the influence of confounding factors (*e.g.,* interpersonal differences such as computer experience, familiarity with spatial orientation in three-dimensional games) increases, which can lead to biased results and reduce internal validity.

The advantage of the method outlined in the HoneyComb protocol is that it can be combined with computer simulation models and used as a paradigm to empirically test if collective patterns found in the computer simulations also hold for behavior in groups of humans. To enhance the external validity of such tests, participants should be asked in the post-test phase questionnaire if they felt sufficiently and humanly represented by their avatars and whether they were able to perceive their co-players as human actors. The protocol specifies the physical presence of the co-players sitting in workstations beside each other (even though the protocol parameters preclude sensory auditory or visual communication) in order to enhance these feelings of human embodiment.

In sum, the methods applied by the HoneyComb approach outlined in the protocol's pre-test, test, and post-test phases provide a novel paradigm to investigate basic mechanisms of collective phenomena such as group coordination, leadership, and intra-group differentiat*n.* The method's most important limitation is its vulnerability to human error by the recruiters, particularly if they are not stringent enough in ensuring that participants do not communicate with each other during the pre-test and test phases.
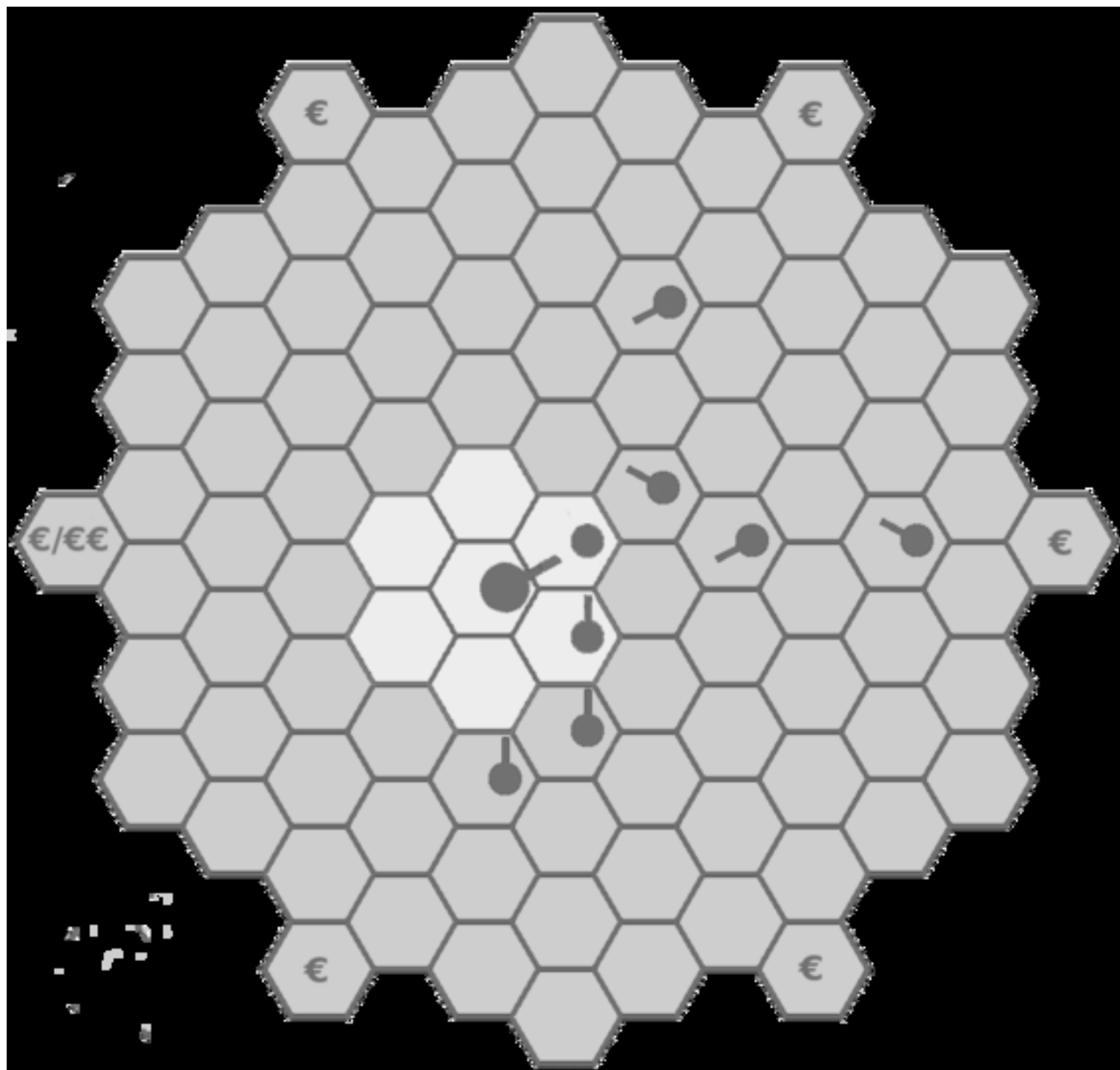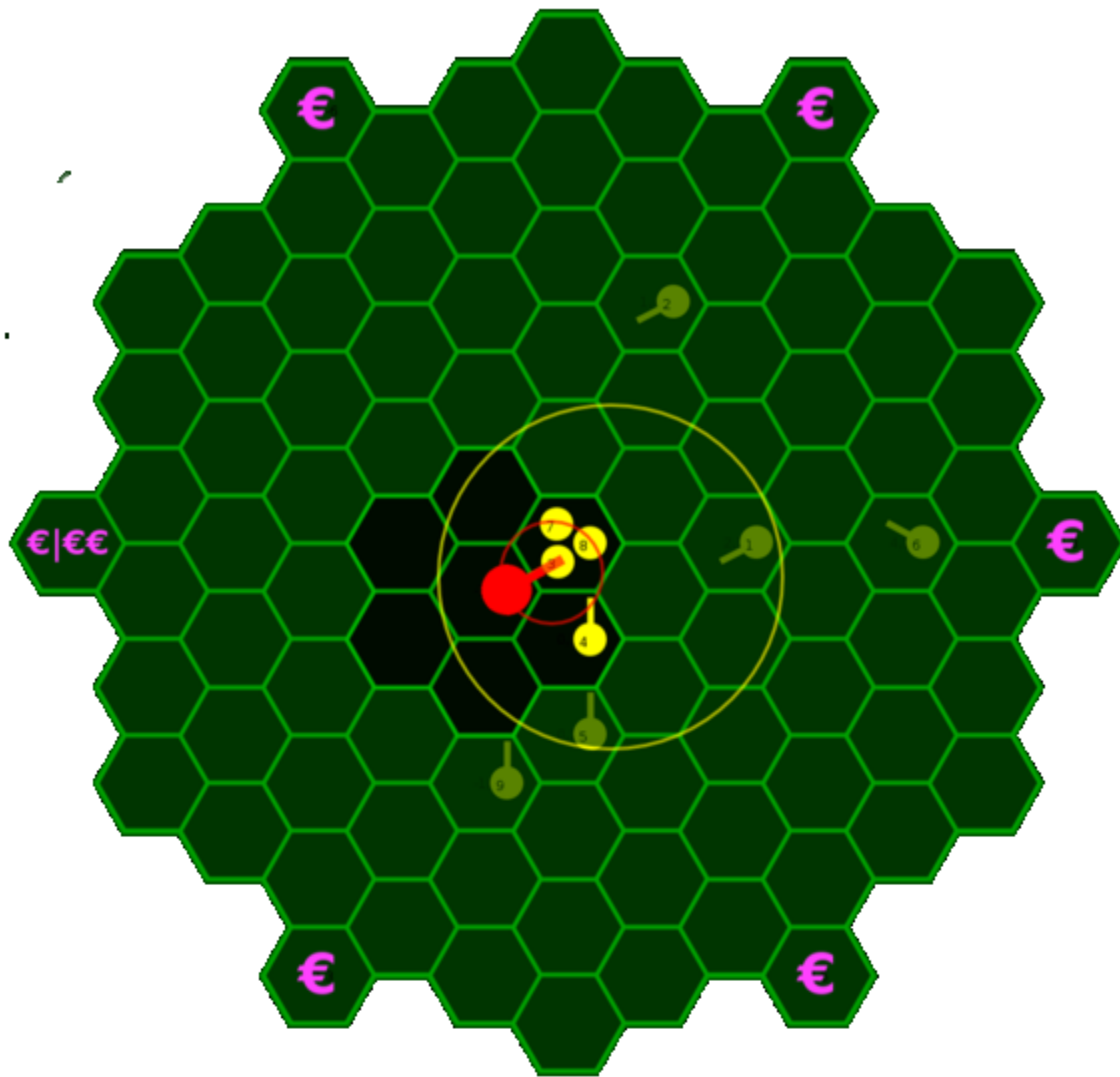
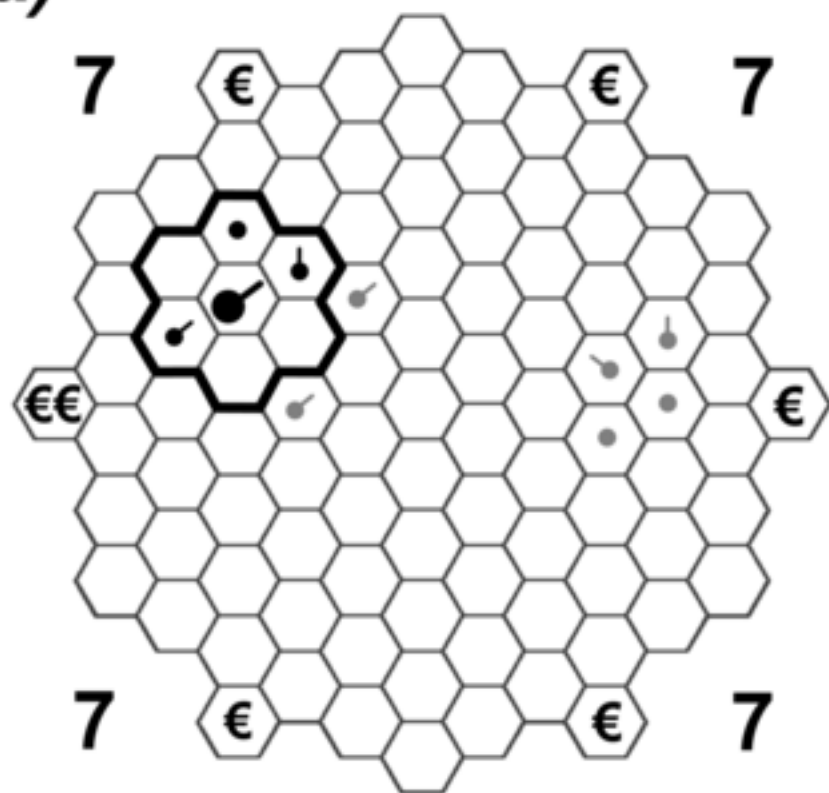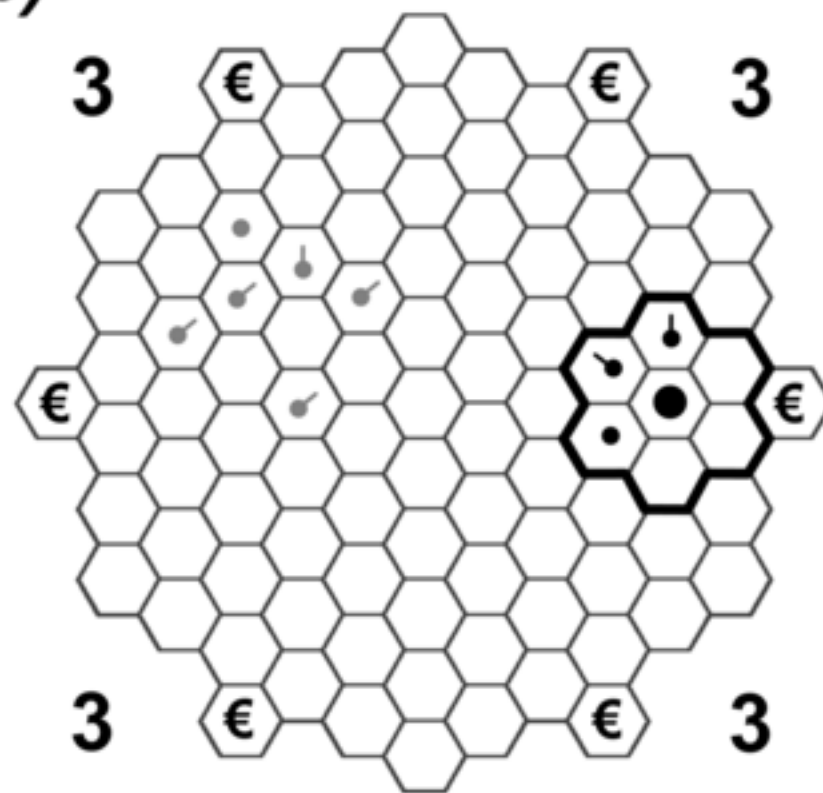**DISCLOSURES:**
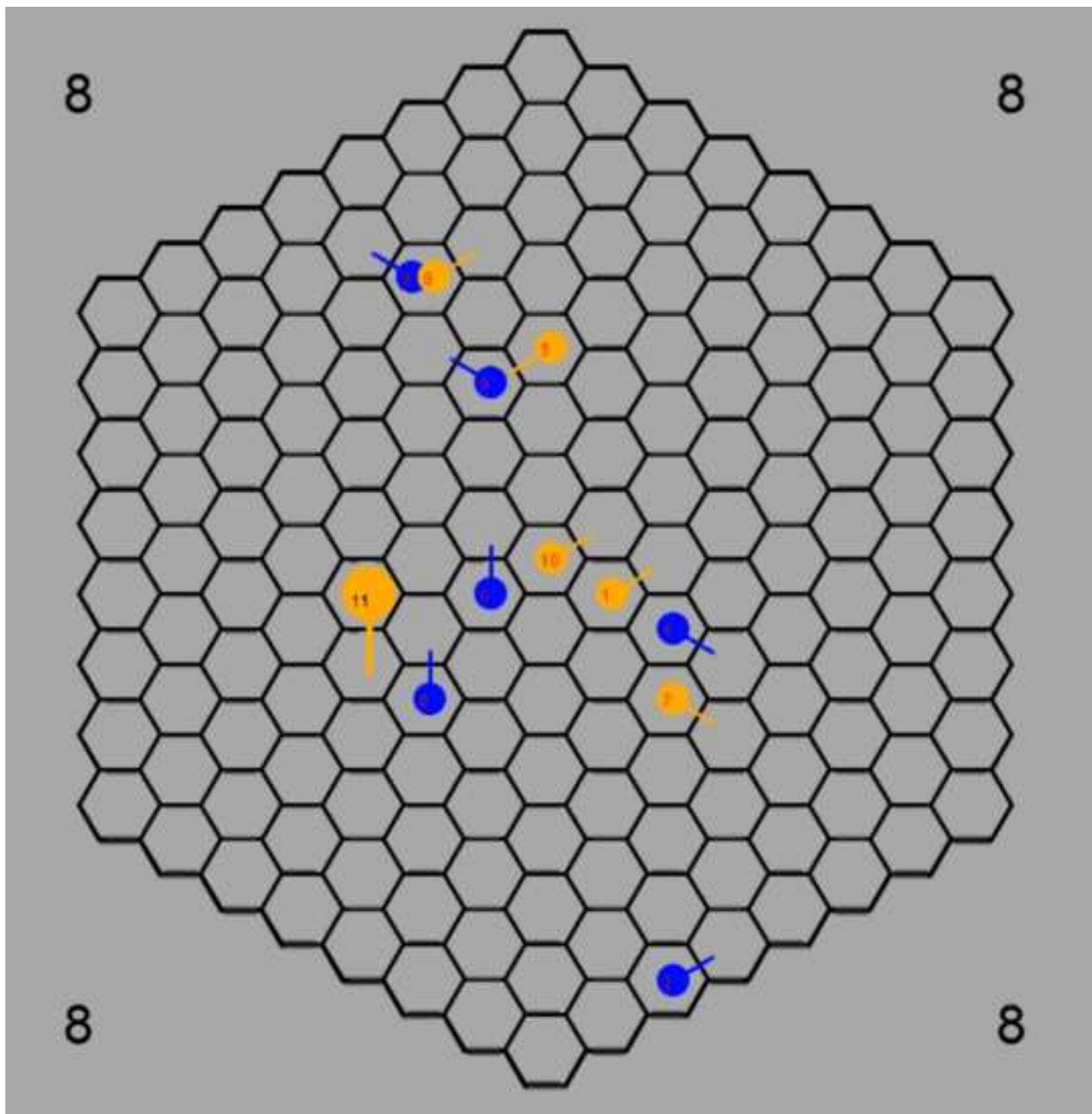The authors have nothing to disclose.

REFERENCES:
1.	Boos, M., Pritz, J., Lange, S., Belz, M. Leadership in Moving Human Groups. *PLoS Computational Biology*. **10** (4), 1003541 (2014).
2.	Moussaid, M., Garnier, S., Theraulaz, G., Helbing, D. Collective information processing and pattern formation in swarms, flocks, and crowds. *Topics in Cognitive Science.* **1** (3), 469-497 (2009).
3.	Sumpter, D. J. T. *Collective Animal Behavior*. Princeton University Press. Princeton. (2010).
4.	Krause, J., *et al.* Fish shoal composition: mechanisms and constraints. *Proceedings - Royal Society. Biological Sciences*. **267** (1456), 2011-2017 (2000).
5.	Camazine, S., *et al. Self-Organization in Biological Systems.* Princeton University Press. Princeton. (2003).
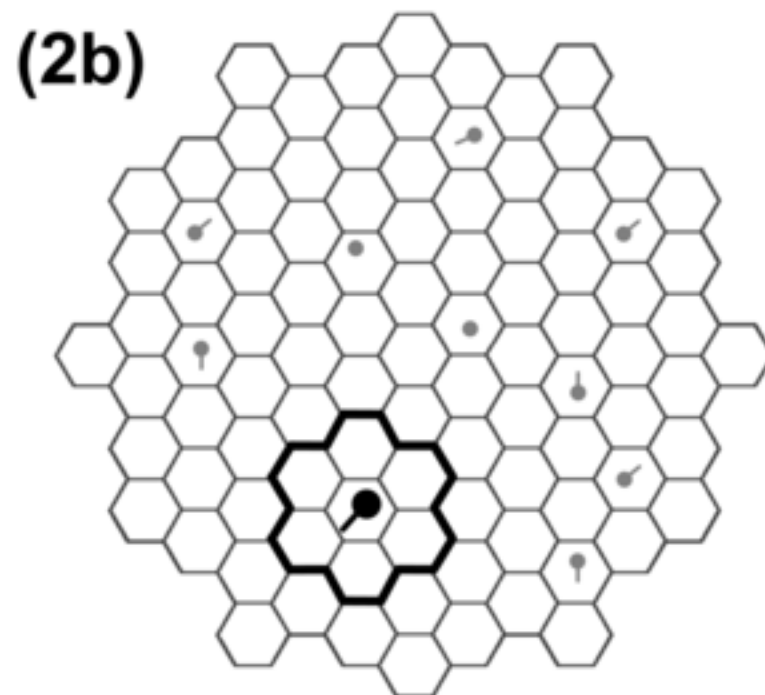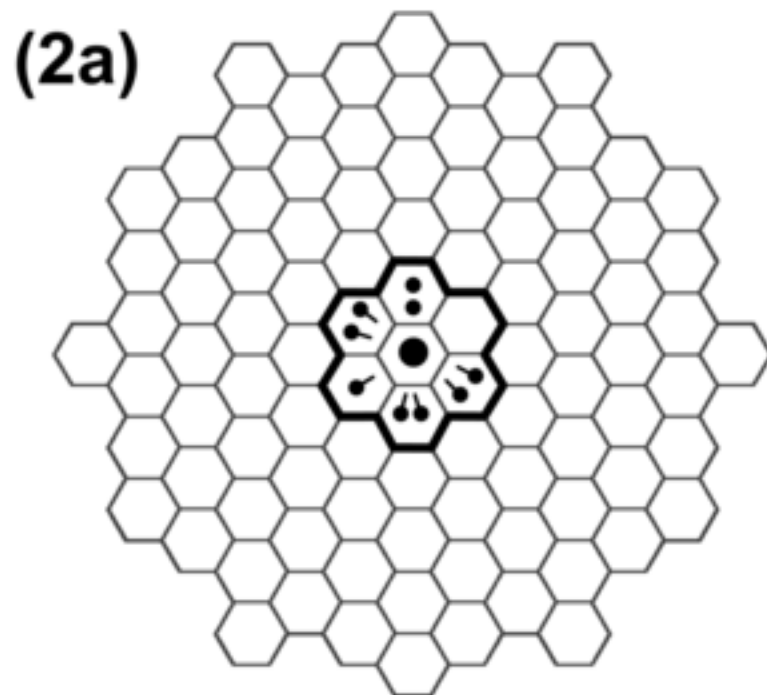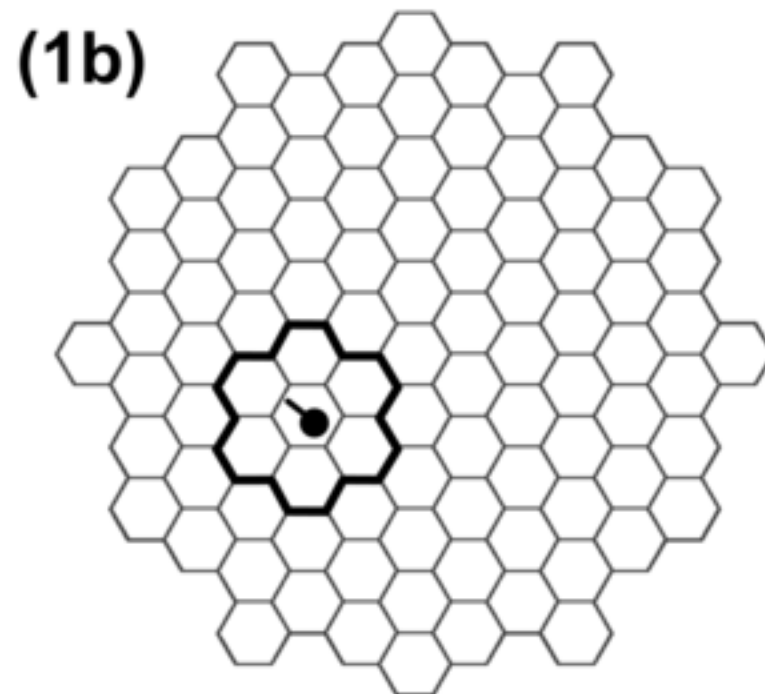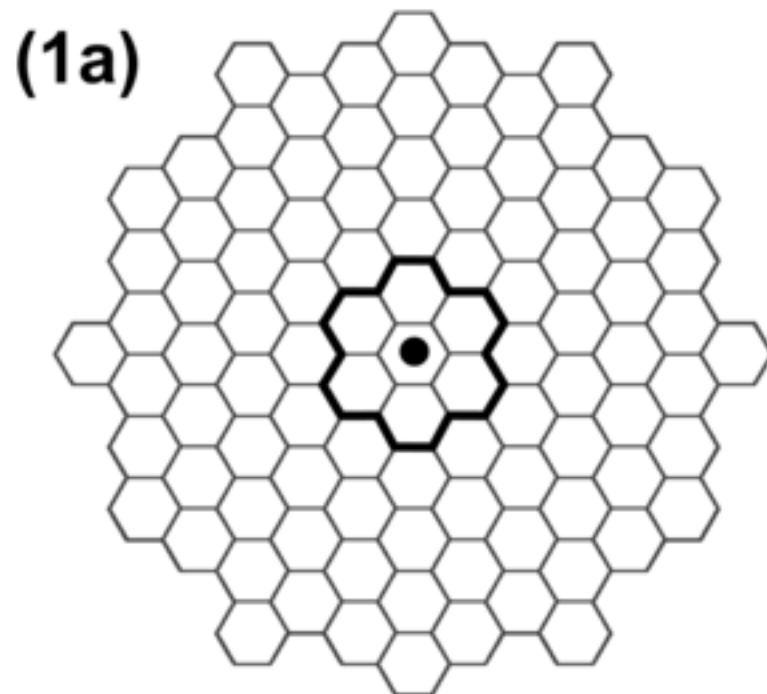
480   6.   King, A. J., Sueur, C., Huchard, E., Cowlishaw, G. A rule-of-thumb based on social affiliation
481   explains collective movements in desert baboons. *Animal Behavior*. **82** (6), 1337-1345 (2011).

482   7.   Fischer, J., Zinner, D. Communication and cognition in primate group movement.
483   *International Journal of Primatology*. **32** (6), 1279-1295 (2011).

484   8.   Couzin, I. D., Krause, J. Self-organization and collective behavior in vertebrates. *Advances
485   in the Study of Behavior*. **32**, 1-75 (2003).

486   9.   Katz, Y., Tunstrøm, K., Ioannou, C. C., Huepe, C., Couzin, I. D. Inferring the structure and
487   dynamics of interactions in schooling fish. *Proceedings of the National Academy of Sciences of
488   the United States of America*. **108** (46), 18720-18725 (2011).

489   10.   Guy, S. J., Curtis, S., Lin, M. C., Manocha, D. Least-effort trajectories lead to emergent
490   crowd behaviors. *Physical Review E: Statistical, Nonlinear, and Soft Matter Physics*. **85** (1), 016110
491   (2012).

492   11.   Shao, W., Terzopoulos, D. Autonomous pedestrians. *Proceedings of the 2005 ACM
493   SIGGRAPH/Eurographics Symposium on Computer Animation.* (2005).

494   12.   Reynolds, C. W. Flocks, herds and schools: A distributed behavioral model. *Seminal
495   Graphics*. ACM, 273-282.

496   13.   Pelechano, N., Allbeck, J. M., Badler, N.I. Controlling individual agents in high-density
497   crowd simulation. *Proceedings of the 2007 ACM SIGGRAPH/Eurographics Symposium on
498   Computer Animation*. 99-108 (2007).

499   14.   Helbing, D., Molnár, P., Farkas, I. J., Bolay, K. Self-organizing pedestrian movement.
500   *Environment and Planning B: Planning and Design*. **28** (3), 361-383 (2001).

501   15.   Dyer, J. R. G., Johansson, A., Helbing, D., Couzin, I. D., Krause, J. Leadership, consensus
502   decision making and collective behavior in humans. *Philosophical Transactions - Royal Society.
503   Biological Sciences*. **364** (1518), 781-789 (2009).

504   16.   Moussaid, M., Schinazi, V. R., Kapadia, M., Thrash, T. Virtual Sensing and Virtual
505   Reality: How New Technologies can Boost Research on Crowd Dynamics. *Frontiers in Robotics
506   and AI*. doi: 10.3389/frobt.2018.00082 (2018).

507   17.   Belz, M., Pyritz, L. W., Boos, M. Spontaneous flocking in human groups. *Behavioral
508   Processes*. **92**, 6-14 (2013).

509   18.   Boos, M., Franiel, X., Belz, M. Competition in human groups - Impact on group cohesion,
510   perceived stress and outcome satisfaction. *Behavioral Processes*. **120**, 64-68 (2015).

511   19.   Boos, M., Li, W., Pritz, J. Patterns of Group Movement on a Virtual Playfield: Empirical
512   and Simulation Approaches. *Social Network Analysis: Interdisciplinary Approaches and Case
513   Studies.* Fu, X., Luo, J.-D., Boos, M., eds. 197-223 (2017).

514   20.   Dyer, J. R. G., *et al.* Consensus decision making in human crowds. *Animal Behavior*. **75** (2),
515   461-470 (2008).

516   21.   Faria, J. J., Dyer, J. R. G., Tosh, C. R., Krause J. Leadership and social information use in
517   human crowds. *Animal Behavior*. **79** (4), 895-901 (2010).

518   22.   Conradt, L. Models in animal collective decision-making: information uncertainty and
519   conflicting preferences. *Interface Focus*. **2** (2), 226-240 (2011).

520   23.   Couzin, I. D., Krause, J., Franks, N. R., Levin, S. A. Effective leadership and decision-making
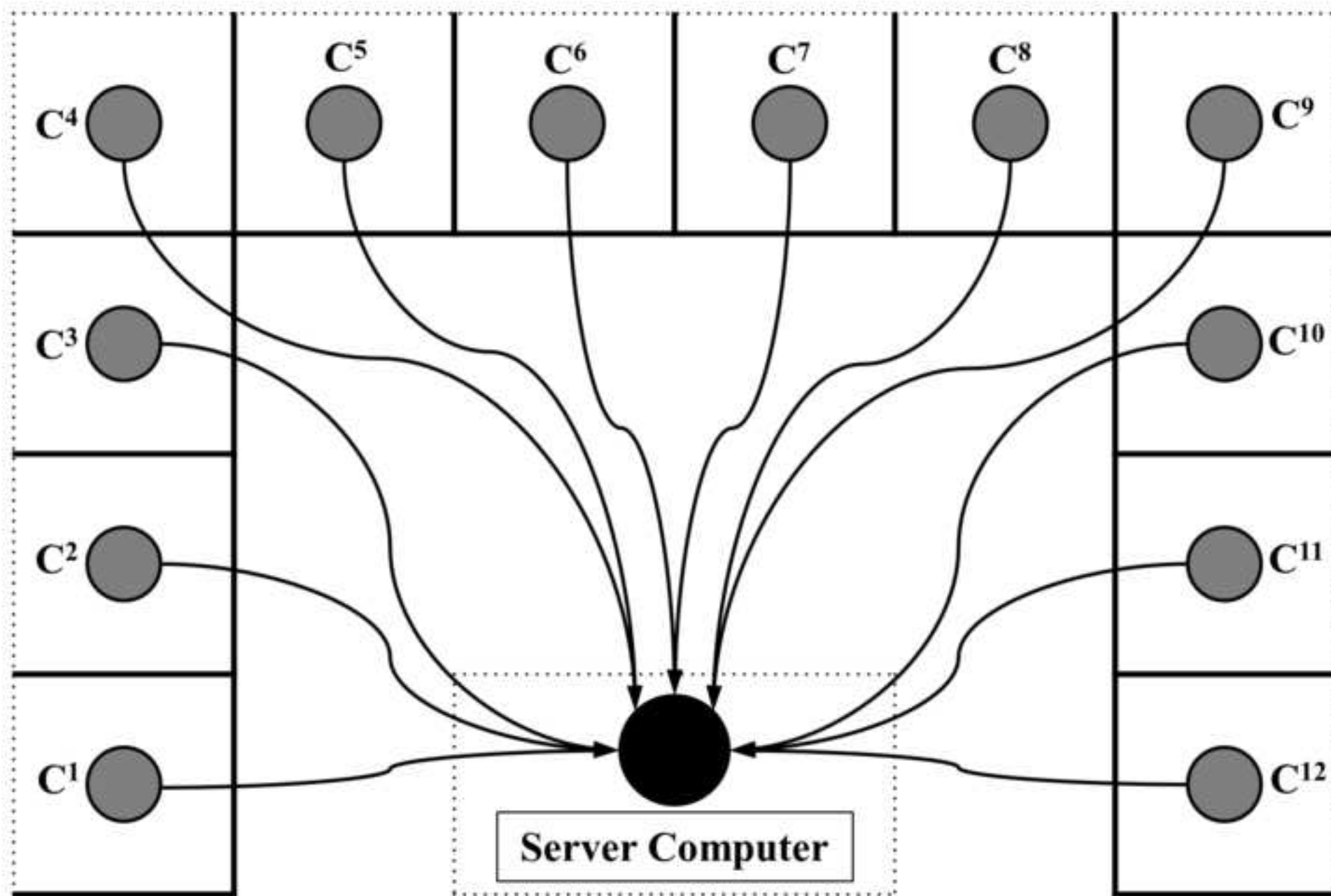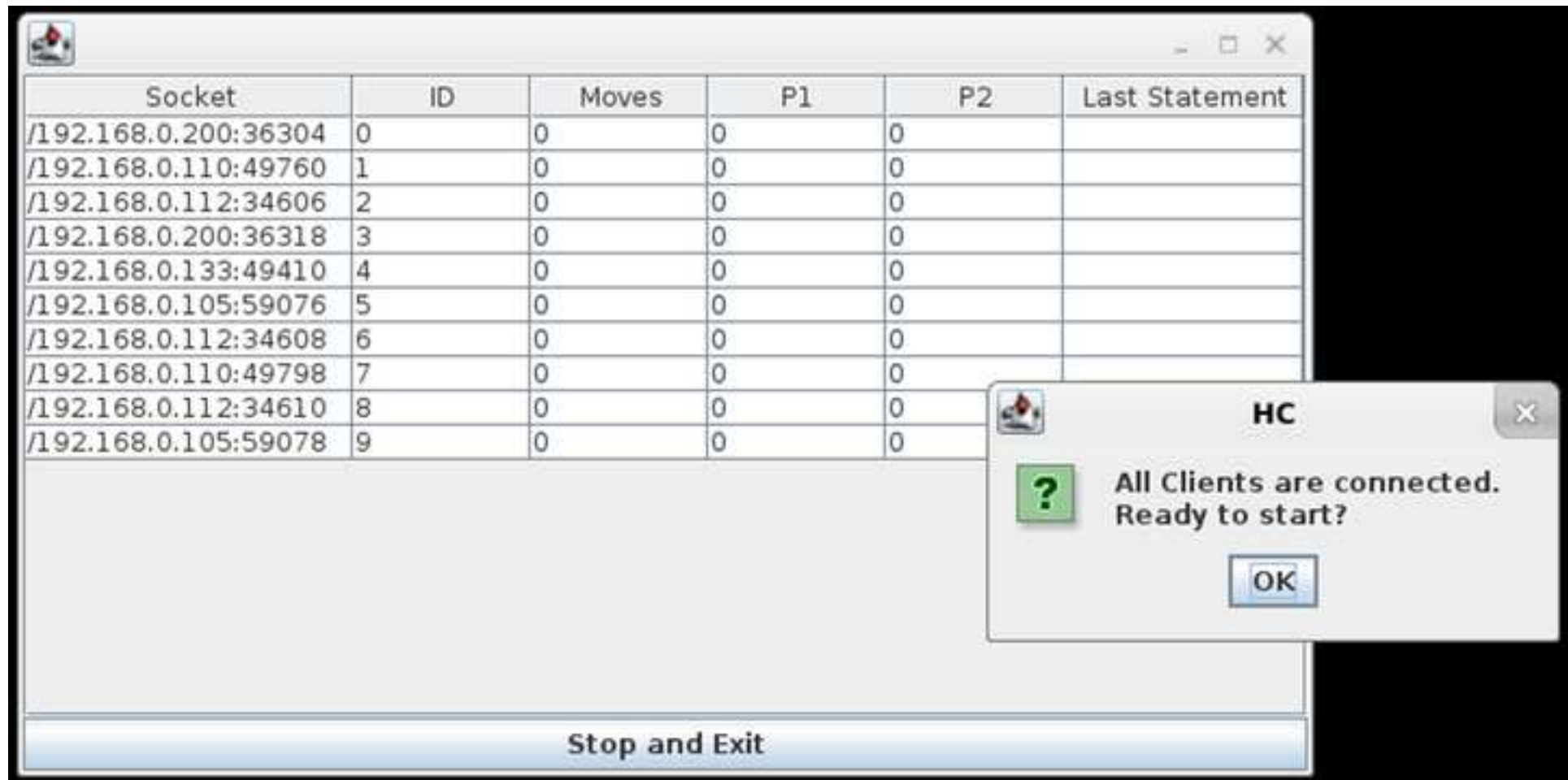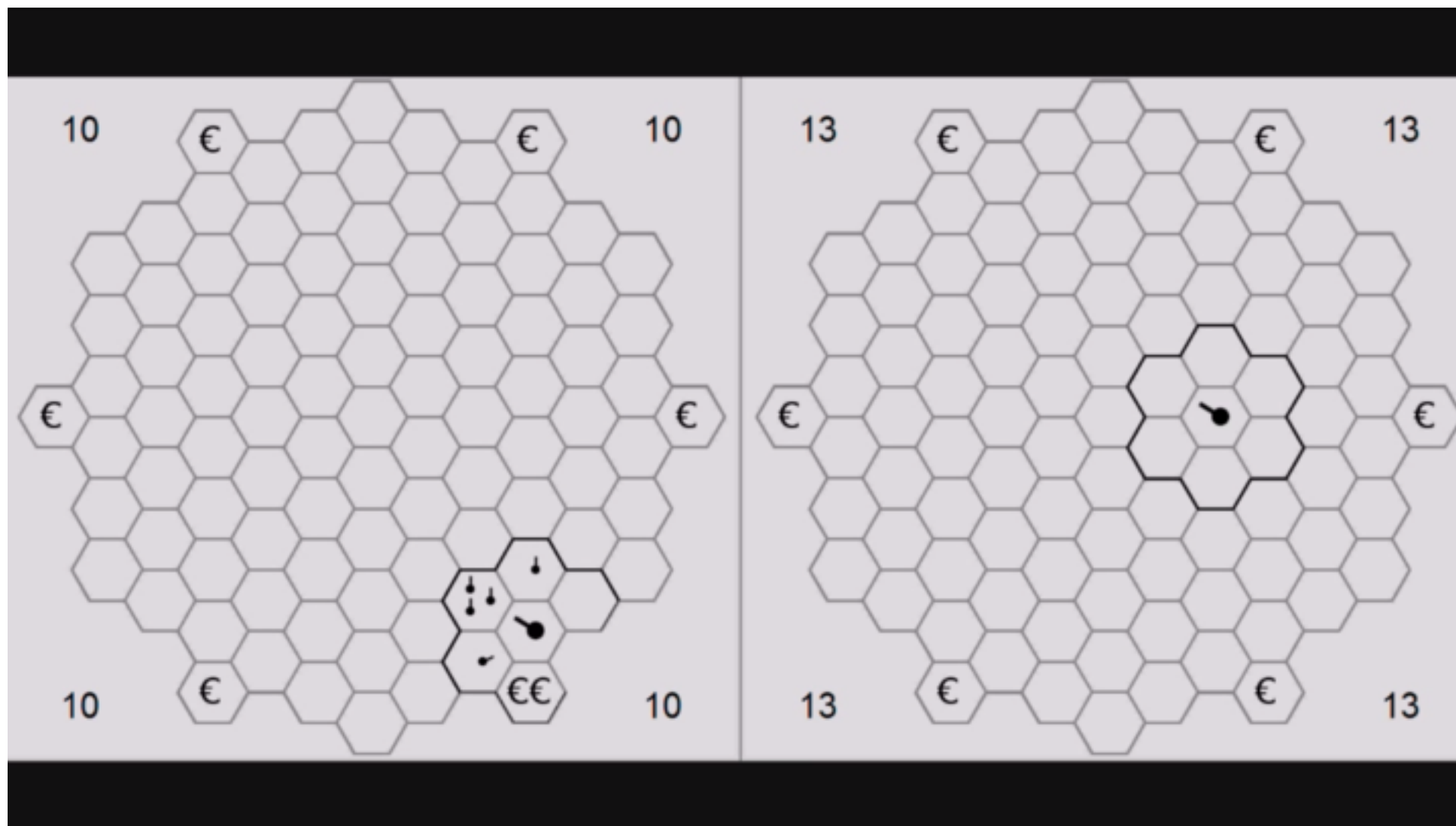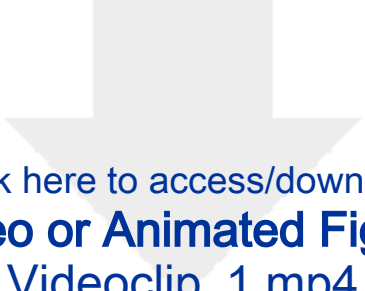521   in animal groups on the move. *Nature*. **433**, 513-516 (2005).

(1a)　(1b)　(2a)　(2b)

Socket	ID	Moves	P1	P2	Last Statement
/192.168.0.200:36304	0	0	0	0	
/192.168.0.110:49760	1	0	0	0	
/192.168.0.112:34606	2	0	0	0	
/192.168.0.200:36318	3	0	0	0	
/192.168.0.133:49410	4	0	0	0	
/192.168.0.105:59076	5	0	0	0	
/192.168.0.112:34608	6	0	0	0	
/192.168.0.110:49798	7	0	0	0	
/192.168.0.112:34610	8	0	0	0	
/192.168.0.105:59078	9	0	0	0	

HC

**All Clients are connected.
Ready to start?**

OK

Stop and Exit
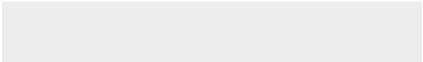
Click here to access/download

Video or Animated Figure

Videoclip_1.mp4

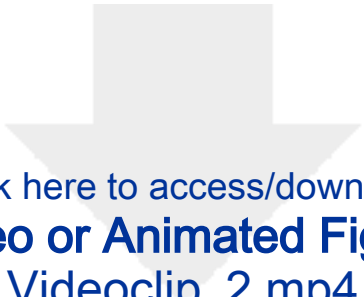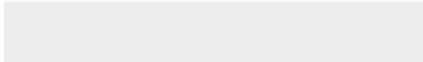Click here to access/download

Video or Animated Figure

Videoclip_2.mp4

Table 1

gnr	time	pid	s1	s2		
	...					
5	14:56:42,281	5	2	2		
5	14:56:42,500	2	3	5		
	...					
5	14:56:44,593	0	3	6	NNug=2	not_moved
5	14:56:44,578	3	2	2		
5	14:56:44,796	7	3	3		
5	14:56:45,125	6	-5	-3		
5	14:56:46,109	1	2	2		
5	14:56:46,281	5	2	2		not_moved
5	14:56:46,765	3	3	3		
5	14:56:47,531	4	2	3		not_moved
5	14:56:48,187	9	3	6	NNug=2	not_moved
5	14:56:48,625	2	3	6	NNug=2	not_moved
5	14:56:48,625	8	3	2		not_moved
5	14:56:48,640	6	-6	-3	NNug=1	
5	14:56:48,640	4	3	4		
5	14:56:48,953	7	3	3		not_moved
5	14:56:49,390	5	3	3		
	...					
5	14:56:52,671	4	3	4		not_moved
5	14:56:52,687	6	-6	-3	NNug=1	not_moved

Name of Material/ Equipment	Company	Catalog Number	Comments/Description
Notebooks			
Partition walls between work stations			
Earplugs			
Equipment for LAN installation			

jove
VISUALIZED EXPERIMENTS

1 Alewife Center #200
Cambridge, MA 02140
tel. 617.945.9051
www.jove.com

ARTICLE AND VIDEO LICENSE AGREEMENT

Title of Article: Honey Comb© – An Experimental Paradigm for Research on Human Collective Behaviour

Author(s): Margarete Boos, Johannes Pritz, Michael Belz

Item 1: The Author elects to have the Materials be made available (as described at http://www.jove.com/publish) via:

☒ Standard Access   ☐ Open Access

Item 2: Please select one of the following items:

☒ The Author is **NOT** a United States government employee.

☐ The Author is a United States government employee and the Materials were prepared in the course of his or her duties as a United States government employee.

☐ The Author is a United States government employee but the Materials were NOT prepared in the course of his or her duties as a United States government employee.

ARTICLE AND VIDEO LICENSE AGREEMENT

1.   **Defined Terms.** As used in this Article and Video License Agreement, the following terms shall have the following meanings: "**Agreement**" means this Article and Video License Agreement; "**Article**" means the article specified on the last page of this Agreement, including any associated materials such as texts, figures, tables, artwork, abstracts, or summaries contained therein; "**Author**" means the author who is a signatory to this Agreement; "**Collective Work**" means a work, such as a periodical issue, anthology or encyclopedia, in which the Materials in their entirety in unmodified form, along with a number of other contributions, constituting separate and independent works in themselves, are assembled into a collective whole; "**CRC License**" means the Creative Commons Attribution-Non Commercial-No Derivs 3.0 Unported Agreement, the terms and conditions of which can be found at: http://creativecommons.org/licenses/by-nc-nd/3.0/legalcode; "**Derivative Work**" means a work based upon the Materials or upon the Materials and other pre-existing works, such as a translation, musical arrangement, dramatization, fictionalization, motion picture version, sound recording, art reproduction, abridgment, condensation, or any other form in which the Materials may be recast, transformed, or adapted; "**Institution**" means the institution, listed on the last page of this Agreement, by which the Author was employed at the time of the creation of the Materials; "**JoVE**" means MyJove Corporation, a Massachusetts corporation and the publisher of The Journal of Visualized Experiments; "**Materials**" means the Article and / or the Video; "**Parties**" means the Author and JoVE; "**Video**" means any video(s) made by the Author, alone or in conjunction with any other parties, or by JoVE or its affiliates or agents, individually or in collaboration with the Author or any other parties, incorporating all or any portion of the Article, and in which the Author may or may not appear.

2.   **Background.** The Author, who is the author of the Article, in order to ensure the dissemination and protection of the Article, desires to have the JoVE publish the Article and create and transmit videos based on the Article. In furtherance of such goals, the Parties desire to memorialize in this Agreement the respective rights of each Party in and to the Article and the Video.

3.   **Grant of Rights in Article.** In consideration of JoVE agreeing to publish the Article, the Author hereby grants to JoVE, subject to **Sections 4** and **7** below, the exclusive, royalty-free, perpetual (for the full term of copyright in the Article, including any extensions thereto) license (a) to publish, reproduce, distribute, display and store the Article in all forms, formats and media whether now known or hereafter developed (including without limitation in print, digital and electronic form) throughout the world, (b) to translate the Article into other languages, create adaptations, summaries or extracts of the Article or other Derivative Works (including, without limitation, the Video) or Collective Works based on all or any portion of the Article and exercise all of the rights set forth in (a) above in such translations, adaptations, summaries, extracts, Derivative Works or Collective Works and(c) to license others to do any or all of the above. The foregoing rights may be exercised in all media and formats, whether now known or hereafter devised, and include the right to make such modifications as are technically necessary to exercise the rights in other media and formats. If the "Open Access" box has been checked in **Item 1** above, JoVE and the Author hereby grant to the public all such rights in the Article as provided in, but subject to all limitations and requirements set forth in, the CRC License.

612542.6   For questions, please contact us at submissions@jove.com or +1.617.945.9051.

4. **Retention of Rights in Article.** Notwithstanding the exclusive license granted to JoVE in **Section 3** above, the Author shall, with respect to the Article, retain the non-exclusive right to use all or part of the Article for the non-commercial purpose of giving lectures, presentations or teaching classes, and to post a copy of the Article on the Institution's website or the Author's personal website, in each case provided that a link to the Article on the JoVE website is provided and notice of JoVE's copyright in the Article is included. All non-copyright intellectual property rights in and to the Article, such as patent rights, shall remain with the Author.

5. **Grant of Rights in Video – Standard Access.** This **Section 5** applies if the "Standard Access" box has been checked in **Item 1** above or if no box has been checked in **Item 1** above. In consideration of JoVE agreeing to produce, display or otherwise assist with the Video, the Author hereby acknowledges and agrees that, Subject to **Section 7** below, JoVE is and shall be the sole and exclusive owner of all rights of any nature, including, without limitation, all copyrights, in and to the Video. To the extent that, by law, the Author is deemed, now or at any time in the future, to have any rights of any nature in or to the Video, the Author hereby disclaims all such rights and transfers all such rights to JoVE.

6. **Grant of Rights in Video – Open Access.** This **Section 6** applies only if the "Open Access" box has been checked in **Item 1** above. In consideration of JoVE agreeing to produce, display or otherwise assist with the Video, the Author hereby grants to JoVE, subject to **Section 7** below, the exclusive, royalty-free, perpetual (for the full term of copyright in the Article, including any extensions thereto) license (a) to publish, reproduce, distribute, display and store the Video in all forms, formats and media whether now known or hereafter developed (including without limitation in print, digital and electronic form) throughout the world, (b) to translate the Video into other languages, create adaptations, summaries or extracts of the Video or other Derivative Works or Collective Works based on all or any portion of the Video and exercise all of the rights set forth in (a) above in such translations, adaptations, summaries, extracts, Derivative Works or Collective Works and (c) to license others to do any or all of the above. The foregoing rights may be exercised in all media and formats, whether now known or hereafter devised, and include the right to make such modifications as are technically necessary to exercise the rights in other media and formats. For any Video to which this **Section 6** is applicable, JoVE and the Author hereby grant to the public all such rights in the Video as provided in, but subject to all limitations and requirements set forth in, the CRC License.

7. **Government Employees.** If the Author is a United States government employee and the Article was prepared in the course of his or her duties as a United States government employee, as indicated in **Item 2** above, and any of the licenses or grants granted by the Author hereunder exceed the scope of the 17 U.S.C. 403, then the rights granted hereunder shall be limited to the maximum rights permitted under such statute. In such case, all provisions contained herein that are not in conflict with such statute shall remain in full force and effect, and all provisions contained herein that do so conflict shall be deemed to be amended so as to provide to JoVE the maximum rights permissible within such statute.

8. **Protection of the Work.** The Author(s) authorize JoVE to take steps in the Author(s) name and on their behalf if JoVE believes some third party could be infringing or might infringe the copyright of either the Author's Article and/or Video.

9. **Likeness, Privacy, Personality.** The Author hereby grants JoVE the right to use the Author's name, voice, likeness, picture, photograph, image, biography and performance in any way, commercial or otherwise, in connection with the Materials and the sale, promotion and distribution thereof. The Author hereby waives any and all rights he or she may have, relating to his or her appearance in the Video or otherwise relating to the Materials, under all applicable privacy, likeness, personality or similar laws.

10. **Author Warranties.** The Author represents and warrants that the Article is original, that it has not been published, that the copyright interest is owned by the Author (or, if more than one author is listed at the beginning of this Agreement, by such authors collectively) and has not been assigned, licensed, or otherwise transferred to any other party. The Author represents and warrants that the author(s) listed at the top of this Agreement are the only authors of the Materials. If more than one author is listed at the top of this Agreement and if any such author has not entered into a separate Article and Video License Agreement with JoVE relating to the Materials, the Author represents and warrants that the Author has been authorized by each of the other such authors to execute this Agreement on his or her behalf and to bind him or her with respect to the terms of this Agreement as if each of them had been a party hereto as an Author. The Author warrants that the use, reproduction, distribution, public or private performance or display, and/or modification of all or any portion of the Materials does not and will not violate, infringe and/or misappropriate the patent, trademark, intellectual property or other rights of any third party. The Author represents and warrants that it has and will continue to comply with all government, institutional and other regulations, including, without limitation all institutional, laboratory, hospital, ethical, human and animal treatment, privacy, and all other rules, regulations, laws, procedures or guidelines, applicable to the Materials, and that all research involving human and animal subjects has been approved by the Author's relevant institutional review board.

11. **JoVE Discretion.** If the Author requests the assistance of JoVE in producing the Video in the Author's facility, the Author shall ensure that the presence of JoVE employees, agents or independent contractors is in accordance with the relevant regulations of the Author's institution. If more than one author is listed at the beginning of this Agreement, JoVE may, in its sole

![jove logo] 1 Alewife Center #200
Cambridge, MA 02140
tel. 617.945.9051
www.jove.com

discretion, elect not take any action with respect to the Article until such time as it has received complete, executed Article and Video License Agreements from each such author. JoVE reserves the right, in its absolute and sole discretion and without giving any reason therefore, to accept or decline any work submitted to JoVE. JoVE and its employees, agents and independent contractors shall have full, unfettered access to the facilities of the Author or of the Author's institution as necessary to make the Video, whether actually published or not. JoVE has sole discretion as to the method of making and publishing the Materials, including, without limitation, to all decisions regarding editing, lighting, filming, timing of publication, if any, length, quality, content and the like.

12. **Indemnification.** The Author agrees to indemnify JoVE and/or its successors and assigns from and against any and all claims, costs, and expenses, including attorney's fees, arising out of any breach of any warranty or other representations contained herein. The Author further agrees to indemnify and hold harmless JoVE from and against any and all claims, costs, and expenses, including attorney's fees, resulting from the breach by the Author of any representation or warranty contained herein or from allegations or instances of violation of intellectual property rights, damage to the Author's or the Author's institution's facilities, fraud, libel, defamation, research, equipment, experiments, property damage, personal injury, violations of institutional, laboratory, hospital, ethical, human and animal treatment, privacy or other rules, regulations, laws, procedures or guidelines, liabilities and other losses or damages related in any way to the submission of work to JoVE, making of videos by JoVE, or publication in JoVE or elsewhere by JoVE. The Author shall be responsible for, and shall hold JoVE harmless from, damages caused by lack of sterilization, lack of cleanliness or by contamination due to

the making of a video by JoVE its employees, agents or independent contractors. All sterilization, cleanliness or decontamination procedures shall be solely the responsibility of the Author and shall be undertaken at the Author's expense. All indemnifications provided herein shall include JoVE's attorney's fees and costs related to said losses or damages. Such indemnification and holding harmless shall include such losses or damages incurred by, or in connection with, acts or omissions of JoVE, its employees, agents or independent contractors.

13. **Fees.** To cover the cost incurred for publication, JoVE must receive payment before production and publication of the Materials. Payment is due in 21 days of invoice. Should the Materials not be published due to an editorial or production decision, these funds will be returned to the Author. Withdrawal by the Author of any submitted Materials after final peer review approval will result in a US$1,200 fee to cover pre-production expenses incurred by JoVE. If payment is not received by the completion of filming, production and publication of the Materials will be suspended until payment is received.

14. **Transfer, Governing Law.** This Agreement may be assigned by JoVE and shall inure to the benefits of any of JoVE's successors and assignees. This Agreement shall be governed and construed by the internal laws of the Commonwealth of Massachusetts without giving effect to any conflict of law provision thereunder. This Agreement may be executed in counterparts, each of which shall be deemed an original, but all of which together shall be deemed to me one and the same agreement. A signed copy of this Agreement delivered by facsimile, e-mail or other means of electronic transmission shall be deemed to have the same legal effect as delivery of an original signed copy of this Agreement.

A signed copy of this document must be sent with all new submissions. Only one Agreement is required per submission.

CORRESPONDING AUTHOR

Name: Dr. Margarete Boos

Department: Psychology

Institution: University of Goettingen

Title: ~~House~~ Prof. Dr.

Signature: *[signature]*   Date: July 2, 2018

Please submit a **signed** and **dated** copy of this license by one of the following three methods:
1. Upload an electronic version on the JoVE submission site
2. Fax the document to +1.866.381.2236
3. Mail the document to JoVE / Attn: JoVE Editorial / 1 Alewife Center #200 / Cambridge, MA 02140

612542.6   For questions, please contact us at submissions@jove.com or +1.617.945.9051.

Response to the reviewer's comments and instructions

Again, we perceived the editorial comments to be very helpful. Please see the following list with our detailed responses. All changes we made are marked as track changes within the revised manuscript file.

<u>*Editorial comments*</u>

Editorial comment 1: Please remove the reference here. Please shorten the Summary to be 50 words or less.

    Response: The reference has been removed. The Summary has been shortened to a maximum of 50 words.

Editorial comment 2: Please provide Table 1 as an xls/xlsx instead of a txt file.

    Response: An .xlsx-file is now provided, containing an excerpt of spatio-temporal data of individual movement behavior within a group of 10 players.

Editorial comment 3: Figures are presented out of order. Figure 7 should be numbered before Figure 2 as it is a schematic. Figures 3, 4, 5, 6 should be presented together.

Figure 1 = current Figure 1

Figure 2 = current Figure 3

Figure 3 = current Figure 4

Figure 4 = current Figure 5

Figure 5 = current Figure 6

Figure 6 = current Figure 7

Figure 7 = current Figure 2

    Response: All figures have been renumbered accordingly and are now presented in order. We also added a new figure (Figure 8 now shows the server's user interface, see comment 7), and thus renumbered the former Figure 8 to Figure 9.

Editorial comment 4 (3. Experimental procedure): This is what should be filmed but there are not enough details to film. Please provide more explicit user input commands. How are these steps actually done?

    Response: Please see the following comments and responses for all changes.

Editorial comment 5 (3. Experimental procedure): What actions are done by you to start the program? What command lines are used? It is best if a GUI is used and all user input commands are provided: File | Save | etc.

     Response: We now provide the specific command lines for the server and the client laptops. The server GUI (Graphical User Interface) is now described in the new Figure 8.

Editorial comment 6 (3. Experimental procedure): We need these details here. The manuscript here should be able to stand alone. What are the parameters used here? How is this program configured?

     Response: We clarified that the described experimental procedure for JoVE focuses on the game used by Boos et al. (2014), which is now described in more detail (see other comments).

Editorial comment 7 (3. Experimental procedure): Please provide the details of this GUI.

     Response: Please see new Figure 8 for all details.

Editorial comment 8 (3. Experimental procedure): Instructions from where?

     Response: We now describe that instructions are stored as editable html-files within the program folder.

Editorial comment 9 (3. Experimental procedure): What are the experimental conditions used here?

     Response: More specific detail is given (see Note 3.1.5) about the two experimental conditions used by Boos et al. (2014), as well as the specific inputs for the server configuration file.

Editorial comment 10 (3. Experimental procedure): Is the program run twice? How long does the program take? What is the sample size? How many 10-12 person groups are used?

     Response: We now clarify that each participant can only partake once, due to possible results bias when a game is repeated. We also give details about the duration of the described game (5–10 min with instructions), and the sample size used by Boos et al. (2014 – 40 groups à 10 persons).

Editorial comment 11 (3. Experimental procedure): How many subgames are there?

     Response: There is only one subgame that was used by Boos et al. (2014) and is described within the experimental procedure (please also see editorial comment 6).

Editorial comment 12 (4. Post-Test Phase): Where are these questionnaires?

Response: Optional questionnaires can be offered as stand-alone html-files.

Editorial comment 13 (Discussion): You have not explicitly explained where the environmental affordance information is semantically embedded so I am assuming it is embedded in the on-screen instructions.

Response: We added a sentence where we say, that the affordances are described in the on-screen instructions read by the participants before the game started.