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OUTLOOK

The promise of cyborg intelligence

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Summary Yu et al. (2016) demonstrated that algorithms designed to find efficient routes in standard mazes can be integrated with the natural processes controlling rat navigation and spatial choices, and they pointed out the promise of such "cyborg intelligence" for biorobotic applications. Here, we briefly describe Yu et al.'s work, explore its relevance to the study of comparative cognition, and indicate how work involving cyborg intelligence would benefit from interdisciplinary collaboration between behavioral scientists and engineers.

Keywords Cyborg intelligence · Rat cyborgs · Spatial cognition · Biorobotics

Almost 15 years ago, Talwar et al. (2002) showed that rats' movements can be controlled using electrodes implanted in somatosensory cortex as stimulus cues and in the medial forebrain bundle as reinforcement. Yu et al. (2016) demonstrated that the Talwar et al. technique can be expanded to produce "cyborgs" by integrating the intrinsic spatial navigation abilities of rats with artificial intelligence. They outlined the promise of such "cyborg intelligence" for biorobotic applications.

Yu et al. (2016) compared the performance of rats, a maze-solving algorithm, and cyborgs in a multiple-unit (10 × 10 units) maze. For each agent on each trial, the maze configuration was unique, but the start and goal locations (in opposite corners of the maze) were common. The algorithm used information about the locations of the walls in previously visited cells (units) of the maze and made choices by sampling systematically from the cells adjacent to the current cell until a reachable cell was located that did not lead only to dead ends. The performance of this algorithm was compared to the performance of both rats and rat cyborgs, where the cyborgs were rats controlled using the Talwar et al. (2002) technique so as to avoid choices of cells leading to dead ends (just as the algorithm did). The cyborgs were additionally controlled to move toward any cells that corresponded to unique paths to the goal (as determined by the walls experienced in visited cells) and to avoid "loops" (cases in which the algorithm would otherwise lead to a recursive sequence of choices).

Rat cyborgs generally outperformed both rats and the algorithm. Some complexities are involved in interpreting these results, however. The cyborgs were the same rats tested without the Talwar procedure, and they were all tested as cyborgs after being tested as noncyborgs (this experimental confound was somewhat ameliorated by additional testing). It is also not clear how completely the cyborgs followed the instructions provided by the algorithm. Finally, some details of the relationship between the algorithms used in isolation and as part of the cyborgs likewise complicate matters. Although these complexities make a direct comparison of the cyborg performance to that of the rats (and of the algorithm) difficult, it seems likely that the cyborg performance reflects a combination of tendencies that are part of the algorithm and others that are intrinsic to rat spatial behavior.

Cyborg behavior that includes artificial intelligence could take the study of behavioral and cognitive processes in several new directions. Formal psychological models (algorithms) are often tested by comparing their performance to that of humans or animals (Fig. 1, top panel). However, cyborg performance is jointly determined by an algorithm and by natural processes. In principle, a comparison of cyborg performance to the performance of the algorithm should reveal any elements of behavior that cannot be accounted for by the algorithm, whereas a comparison of cyborg performance to the performance of unmodified rats should isolate behavior the model can account for (Fig. 1, bottom panel). For example, Yu et al.'s (2016) cyborg algorithm includes the ability to integrate knowledge about the locations of walls in previously visited cells, such that cells leading to dead ends from both visited and unvisited cells can be determined. Yu et al. made no claim about whether rats have this ability (though in fact, they imply that this is one of the features that should improve cyborg performance over that of ordinary rats), but a comparison of the cyborgs' tendency to avoid dead ends to that of rats would provide evidence regarding the extent to which such integration occurs in rats. On the other hand, a performance feature that rats are likely to have that the algorithm does not relates to the fact that the maze's start and goal cell locations are invariant. Several known features of rat

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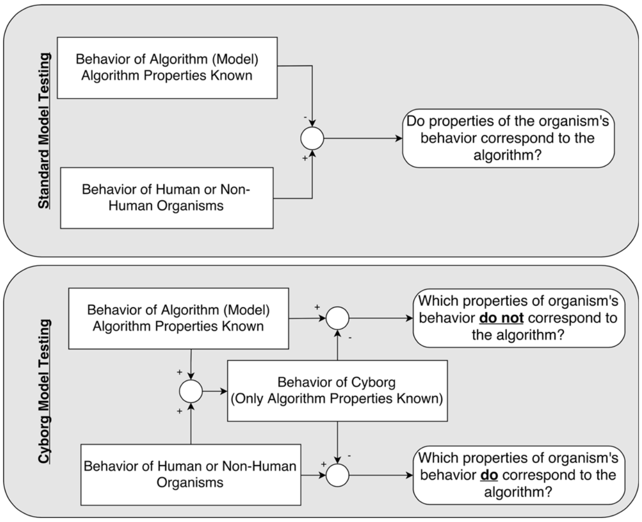

Fig. 1 Standard model testing (*top panel*) in which the behavior of the model and organism is compared. Cyborg behavior is produced by a combination of the model and the organism. Cyborg behavior can then be compared to that driven by either of the mechanisms alone, to identify properties of behavior that do and do not correspond to the model (*bottom panel*)

navigation (e.g., path integration and allocentric spatial cue use; see Gallistel, 1990) predict a tendency to choose cells to the right and top of the current cell (toward the goal location). A comparison of any similar tendency in cyborgs and the algorithm would reveal whether such a tendency exists and confirm its independence of processes incorporated in the algorithm. More generally, algorithm-based cyborgs could expand formal model testing to comparisons of the behavior of cyborgs, controlled by both rat brains and known algorithms, to the behavior controlled by each of these in isolation.

Behavior is not just the output of psychological processes; in many cases, behavior elicits or modulates subsequent behavior, in various forms of feedback loops. Operant chains are a well-known example. An example in the context of spatial behavior is path integration (see, e.g., Etienne & Jeffery, 2004). According to this idea, animals integrate information about the distance and direction of their own movement in order to locate the point from which they started the journey or to determine spatial locations and their relations along the way. Is the source of this information downstream from motor cortex (e.g., proprioceptive), or does it come from earlier processes related to decisions and the planning of motor behavior? Because cyborgs can be manipulated to move independently of other factors, they can be used to vary the behavior that feeds into cognitive systems in ways that are not otherwise possible. Would a rat cyborg, when released from control by an algorithm, be able to find its way back to a starting location, or does path integration require that the movement be under the control of the rat? Might this depend on the extent to which the algorithm mimics the natural behavioral tendencies of the rat? The answers to such questions could reveal the nature of the information that feeds into the path integration system. More generally, the ability to bypass the systems that control rat spatial choices and navigation provides a means of manipulating behaviors that are part of feedback loops in behavioral control systems.

Continued study of cyborg intelligence also has the potential to foster productive collaboration between behavioral scientists and roboticists. Modern mobile robots feature sophisticated estimation and path-planning capabilities that may prove useful in cyborg research for investigating particular functions of spatial memory, route planning, and localization. These include Bayesian mapping and localization algorithms (Thrun, Burgard, & Fox, 2005). In robots, these features drive decision-making in feedback loops at various temporal and organizational scales. Investigating the permutations of cyborg intelligence with more complex algorithms in the loop could shed light on details of animal cognition not accessible with traditional experimental methodology.

In particular, Yu et al.'s (2016) work indicates that a rat's performance in a maze might be improved simply by bypassing certain portions of the rat's normal cognitive function in a "plug-and-play" paradigm, but their work foreshadows a larger opportunity to tighten the coupling between animal and algorithm. Specifically, using rat behaviors (e.g., head orientation, rearing) or physiological changes (e.g., the neural activity associated with motor control) as feedback in an adaptive mapping or navigation system might produce a truly symbiotic relationship between animal and machine. Naturally, introducing this type of two-way communication and learning could improve cyborg performance. However, it could also afford opportunities to deepen the cyborg model-testing paradigm in Fig. 1 to answer questions about whether, when, and how cyborg and biological system performance converge.

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