

In this PhD thesis, Sena has provided evidence that humans and rodents are able to do similar tasks involving time-keeping. Further, she showed that both species are able to judge the quality of their performance even in the absence of explicit feedback from the world (Paper 1). This kind of "temporal error monitoring" judgment constitutes an example of meta-cognition, the ability to perceive and reason about one's own cognition. Meta-cognition is necessary for evaluating one's own timing when explicit feedback is absent.

The nature of that meta-cognitive process was investigated in Paper 2, in which two opposing hypotheses about how motor demands affect temporal meta-cognition were tested. Sena found that increasing motor demands does not make temporal error-monitoring more accurate. That would seem to be predicted by the Motor System hypothesis, in which greater motor variability would provide more instructive feedback for improving performance. Thus it appears that, instead, an internal clock itself is what the temporal error-monitoring (TEM) process is monitoring. That seems like a reasonable conclusion to me, although I don't see strong behavioral evidence in Fig. 2C that the joystick condition was any more demanding than button pressing. The distributions of timing task responses look very similar between button-pressing and joystick-movement. Clearly, the joystick condition is more complex in terms of the number of movements required, however.

Sena has also investigated the neural basis of both timing capability and meta-cognitive assessment of timing performance, using electroencephalography (EEG) and AI-based decoding of EEG data with human participants (Paper 3). She found that EEG frequency bands were all roughly equivalent in supporting decoding of a person's time estimate within a given timing trial of an experiment. In contrast, all bands together were needed to predict a participant's meta-cognitive judgments about their performance. She interpreted this finding as supportive of a distinct neural process involved in meta-cognition relative to the processes needed for simply tracking time. I find that interpretation to be reasonable (in fact, it's hard for me to imagine that not being the case), but I wondered if this finding of needing all frequency bands could be an artifact of TEM data including a lot more noise than just timing data by itself. Since Paper 3 is not yet published, addressing that point could be useful in finalizing it for publication.

A simple example of timing performance is clapping along with a recorded song. When you do this, you can immediately discern whether your clap was late or early relative to the soundtrack: you hear both sounds and can easily compare them.

If you intend to clap in synchrony, but the audio track is muted, then you face a more difficult task. You can clap when you think the beat is occurring, and then you may or may not also be able to use meta-cognition to judge whether your own clap occurred when you intended it to. It is not obvious that even humans must have this ability, let alone rodents. Perhaps when someone claps, the time of that clap just is already their best estimate of when they were supposed to clap.

Therefore it is notable that in Paper 1 of the thesis, not only do humans show evidence of temporal error-monitoring ability, so do rodents. Part of improving motor performance may involve judging whether an action occurred at the time specified by an internal clock. Doing this comparison would seem to require an additional neural/cognitive process for comparing presumably more accurate internal clock signals with sensory feedback signals produced by motor action. Paper 3 supports this hypothesis that a wholly separate, additional meta-cognitive comparison process must be used for such tasks.

Overall, I found the work to be comprehensive, and to provide convergent evidence about meta-cognitive processes involved in timing. I feel that the diversity of Sena's methods involving behavior, statistical modeling and neural recordings have not only provided this convergent evidence, but that they demonstrate Sena is able to use all of these techniques productively to answer important scientific questions.

It is my opinion that the doctoral dissertation meets the conditions specified in art. 187 of the Act of 20 July 2018 - Law on Higher Education and Science (Journal of Laws of 2021, item 478, 619, 1630).