**Key refs on interval timing**

You will need to mention some key reference on interval timing, in particular you might need to explain that interval timing tasks typically include a sample interval which people reproduce, which effectively compares timing within perception (of the sample) to production (of the response). Other paradigms do exist in which ‘reference’ intervals are memorized.

Interval timing research has focussed on locating ‘the clock’ in the brain but importantly it has also been realised that pharmacological state affects timing judgements, with a. focus on dopamine.

Dopaminergic manipulations can affect interval judgement. In the peak intervals procedurev (with rats), dopaminer- gic agonists such as methamphetamine cause underestimation of time intervals (Maricq et al., 1981; Maricq and Church, 1983), whilst dopaminergic agonists such as haloperidol (Maricq and Church, 1983; Rammsayer, 1999; Buhusi and Meck, 2002) cause overestimation of intervals.

Maricq, A. V. and Church, R. M. (1983). The di↵erential e↵ects of haloperidol and methamphetamine on time estimation in the rat. Psychopharmacology (Berl), 79(1):10–5. 0033-3158 (Print) Comparative Study Journal Article Research Support, U.S. Gov’t, Non-P.H.S.

Buhusi, C. V. and Meck, W. H. (2002). Di↵erential e↵ects of metham- phetamine and haloperidol on the control of an internal clock. Behav Neurosci, 116(2):291–7. 0735-7044 (Print) Journal Article.

Rammsayer, T. H. (1999). Neuropharmacological evidence for di↵erent timing mechanisms in humans. The Quarterly Journal of Experimental Psychology Section B, 52(3):273 – 286.

Although it is tempting to explain these dopamine/timing findings in terms of motor arousal, this explanation is unsatisfactory as the same result has been demonstrated in a perceptual matching procedure with rats: rats were trained to respond with one lever for a short interval, and another lever for a long interval, then tested with the two trained intervals plus seven distracter intervals. When tested whilst on methamphetamine, the rats generalised their responses to intervals shorter than the trained intervals; when tested on haloperidol, they generalised to longer intervals (Maricq and Church, 1983).

**The arousal-timing-noradrenaline link**

Noradrenaline drives arousal and arousal affects timing judgements, however to my knowledge no-one has investigated whether noradrenaline affects timing judgements (although there are quite a few studies on the relationship between dopamine and timing judgements

***Key refs on pupil/noradrenaline/arousal***

The classic reference arguing for a relationship between noradrenaline level and performance

[An integrative theory of locus coeruleus-**norepinephrine** function: adaptive gain and optimal performance.](https://pubmed.ncbi.nlm.nih.gov/16022602/)

**Aston-Jones G**, Cohen JD. Annu Rev Neurosci. 2005;28:403-50. doi: 10.1146/annurev.neuro.28.061604.135709.

Evidence that pupil dilation actually does depend on noradrenaline:

[Relationships between **Pupil** Diameter and Neuronal Activity in the Locus Coeruleus, Colliculi, and Cingulate Cortex.](https://pubmed.ncbi.nlm.nih.gov/26711118/)

Joshi S, Li Y, Kalwani RM, Gold JI. Neuron. 2016 Jan 6;89(1):221-34. doi: 10.1016/j.neuron.2015.11.028. Epub 2015 Dec 17.

***Key ref on timing/arousal***

*Arousal affects timing judgements -* Under high levels of arousal, participants perceive time to slow down (although their rate of taking in information does not increase, so Eagleman argues that the ‘clock’ has not actually slowed)

Does Time Really Slow Down during a Frightening Event?

Stetson, Fiesta, Eagleman (2007)

<https://doi.org/10.1371/journal.pone.0001295>

**Explanation of why the question is interesting/timely with respect to the decision-making literature**

Within decision-making research, the explore/exploit trade-off concerns whether people exploit an available situation/reward or try to get into a better situation. This is often modelled in ‘foraging’ paradigms in which participants must decide when to leave a gradually depleting patch of ‘food’ and search for another (explore) – exploring incurs a cost in time and energy, but will ultimately be necessary as the reward available in the current patch is depleted. The optimal decision making process was described in the field of behavioural ecology by Marginal Value Theorem (MVT; Stephens and Krebs 1986).

Here is one of the earliest and best-cited studies exploring this question

Learning the opportunity cost of time in a patch-foraging task

Sara M Constantino Nathaniel D Daw

Cogn Affect Behav Neurosci 2015 Dec;15(4):837-53.

doi: 10.3758/s13415-015-0350-y.

Under MVT, animals must weight the rate of reward in the current patch (number of rewards per time spent exploiting) in the current patch against the background rate of reward (number of rewards per time spent exploiting + travel time). When the rate of reward in the current patch falls below the background rate, they should move on. In fact, most human participants in ‘foraging’ experiments over stay in patches. People with higher levels of noradrenaline overstay less (ie noradrenaline pushes you towards exploring more) which tends to be more ‘optimal’ as it corrects the natural bias to overstay.

Increased locus coeruleus tonic activity causes disengagement from a patch-foraging task

Kane , Vazey, Wilson, Shenhav, Daw, Aston-Jones, Cohen

Cogn Affect Behav Neurosci 2017 Dec;17(6):1073-1083.

doi: 10.3758/s13415-017-0531-y.

Acetylcholine and noradrenaline enhance foraging optimality in humans

Sidorenko, Chung, Grueschow, Quednow Hayward-Könnecke, Jetter, Tobler

Proc Natl Acad Sci U S A 2023 Sep 5;120(36):e2305596120.

doi: 10.1073/pnas.2305596120. Epub 2023 Aug 28.

Studies on the explore/exploit trade-off have focussed on the estimation of reward rate and suggested this may depend on separate mechanisms for the reward rate in the current patch, vs background reward rate. For example they may depend on different dopamine receptors.

Eg

Dopamine Modulates Dynamic Decision-Making during Foraging

Le Heron, Kolling, Plant, Kienast, Janska, Ang, Fallon, Husain, and Apps

J Neurosci. 2020 Jul 1; 40(27): 5273–5282.

In parallel, it has been observed that the pupil is dilated (and noradrenaline released) when people are in an exploratory, as opposed to an exploitative state eg

[Control of entropy in neural models of environmental state.](https://pubmed.ncbi.nlm.nih.gov/30816090/)

Muller TH, Mars RB, Behrens TE, **O'Reilly JX.** Elife. 2019 Feb 28;8:e39404. doi: 10.7554/eLife.39404.

The involvement of noradrenaline is generally interpreted as being to facilitate learning or to promote action;

**However, such studies neglect the underlying dimension of time**. If noradrenaline changed the perception of time (or more specifically, the relative perception of motor time (button press/ travel time), vs sensory time (sound duration/ reward harvesting) this would provide a mechanism for noradrenaline to affect the explore/exploit trade-off that is independent of reward

Therefore, we investigate the relationship between pupil diameter and interval timing in a reward-free task that balances perceptual vs motor timing.