Bayesian cue combination model of intentional binding

Jiajun Ma, Lihan Chen, Konrad Kording, & Kunlin Wei

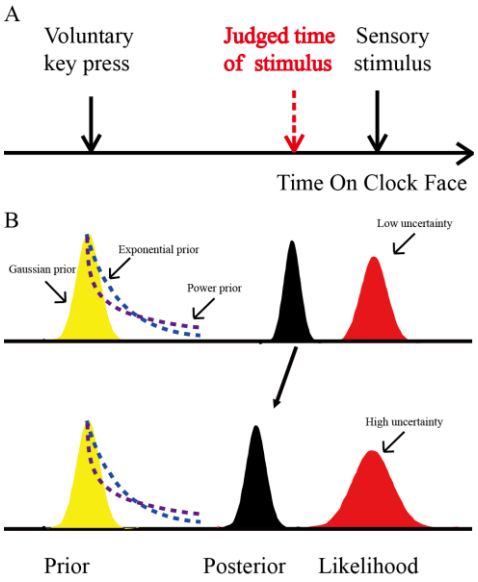
"Intentional binding" is an illusion in timing perception of voluntary action where the perceived duration between a voluntary action and its sensory consequence appears to be shortened (Haggard, 2002). This phenomenon has been extensively studied from the perspective of agency and conscious actions (e.g., Moore, 2012) but a quantitative model is still absent. We hypothesize that the shift of perceived time of the movement consequence is a result of Bayesian cue combination. As most consequences immediately follow the action, our central nervous system should maintain a probabilistic expectation of the incoming event (prior). The stimulus cue (likelihood) is thus combined with this prior for a final estimate of the event, which is shifted earlier in time relative to its true value (Fig 1). This cue combination model further predicts that the more uncertain the stimulus is the more shift occurs, an effect never documented before (Wolpe et al., 2013). Here we test this prediction with psychophysics experiments and also explore possible priors for consequence expectation.

Subjects (n=9) were first examined for their sensory uncertainties about two types of vibrotactile signals. Two signal types, generated by piezoceramic plates, differ in their intensity (weak: frequency 20Hz, amplitude 0.3mm; strong: frequency 160Hz, amplitude 0.8mm). For each signal type, subjects performed a temporal order judgment task for the two signals delivered to their two index finger tips. The temporal uncertainty was higher for the weak signal (SD from fitted psychometric functions: 98.50±- 33.54 vs. 158.65±56.80, $p < 0.001$, Fig 2).

All subjects then performed a classical intentional binding task (Fig 1). While looking at a Libet's clock, subjects randomly initiated a keyboard press (by right hand) and received a vibrotactile signal delivered to their left index finger 250ms later. They were required to report the time of this stimulus by reporting the clock leg position in this *Operant Condition*. The same vibratactile signals above were used. We also tested their timing of stimuli when they are not initiated by their actions (*Baseline Condition*). The intentional binding, specifically the timing shift in perceived consequence, was quantified as the difference in timing between the Operant Condition and the Baseline Condition. We found that the perceived time in the Baseline Condition was delayed but this delay was not affected by likelihood uncertainty (Fig 3a, $p>0.05$), indicating that two types of signals were salient enough for detection. Importantly, the timing shift was significantly larger for the signal with larger likelihood uncertainty (Fig 3b, $p <0.01$), consistent to the prediction of our cue-combination model.

We compared Bayesian cue-combination models with different prior distributions. By assuming a likelihood distribution centered on 250ms with measured variances, we tested which prior distribution --- a Gaussian prior (centered on the time of action, implying that the consequence is still possible to occur earlier than the action due to intrinsic sensory uncertainty), an exponential prior (drops rapidly from the time of action, implying that the consequence is only possible after the actual action) and a power distribution (asymptote with a fat tail, implying a similar expectation as the exponential prior but with a larger probability of late consequences) --- can better explain the average behavior of all subjects (Fig 4). The first two models have only 1 free parameter and the power distribution has two free parameters. We found that Gaussian prior produced the best fit to the data (r^2=0.21).

We conclude that one key finding in intentional binding, the (earlier) shift in timing perception of action consequence, appears to be well explained by a cue combination model. Larger shift is associated with more uncertain (weak) stimuli, a counter-intuitive finding for signal detection theories which usually assume more time is needed (later shift) for detecting/perceiving a weaker signal. By assuming a Bayesian model, we also found that our prior about timing of an action consequence is, perhaps surprisingly, best modeled as a Gaussian distribution.

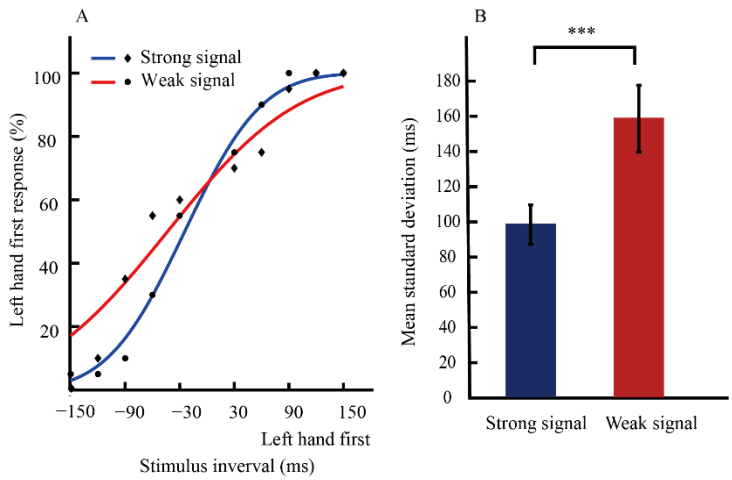


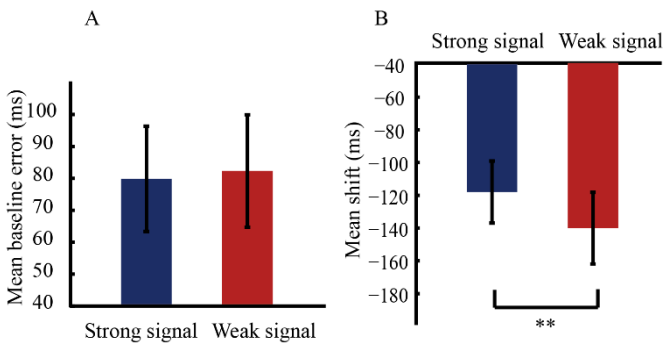
←Figure 1: Intentional binding and a Bayesian cue combination model.

(A) Perceived timing shift of action consequence in intentional binding. Subjects judged time of stimulus earlier than its actual time if it follows a voluntary action. *(B)Bayesian cue combination model for intentional binding.* The final estimate of stimulus time is determined by combing a prior (expectation) and a likelihood (stimulus) distribution. With increasing likelihood uncertainty, the posterior is "drawn" closer to the prior and the timing shift is larger.

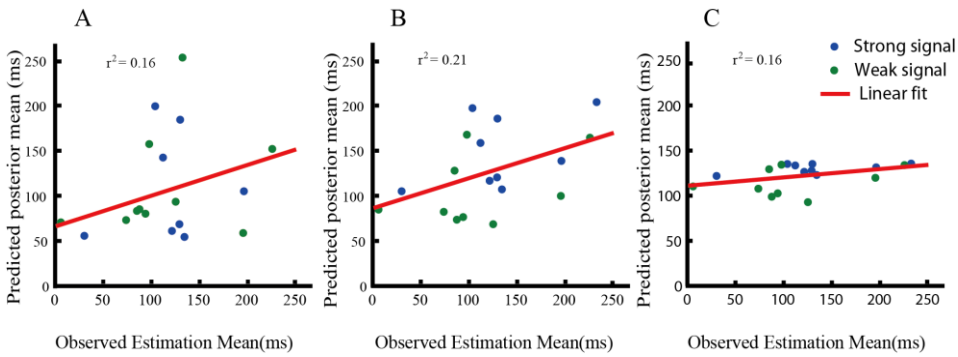
Figure 2: Results of temporal order judgment task. →

(A)The psychometric curve of a typical subject in the temporal order judgment task. The psychometric curves is fitted with a probit function. The Standard Deviation (SD) of the function is used to quantify uncertainty of likelihood. The uncertainty of the weak signal is larger than the strong signal. The SD for this subject is 66.7ms and 112.2ms. *(B) Mean SD from all subjects.* The strong signal has less uncertainty compared with the weak one (p<0.001).





← Figure 3: Results of intentional binding task. *(A)Mean baseline error of two signals.* Without voluntary action, two types of signals produce similar baseline error (p>0.05). *(B) Mean shift in timing (binding effect).* Weak signals lead to significantly more shift in time (p<0.01).



←Figure 4: Comparing predicted posterior mean with observed estimation mean with different priors. *(A)An exponential prior. (B) A Gaussian prior. (C) A prior following a power function.* For each prior, we use data of all participants to fit its parameter(s). The mean of the resulting posterior is compared with the mean estimation. The r^2 is largest when the prior is Gaussian.