

# **Exploring Multi-sensory Integration and Decision-making in PPC using Computational and Animal Models**

*Sophie Sackstein*

In this paper, I hope to explore the mechanisms that underlie the decision making in multi-sensory tasks, such as those explored by Churchland and colleagues. The ability to assess stimuli and learn in a multisensory paradigm is dependent upon the neural circuits that adapt to new behaviors. Current research has focused on testing a rodent model in order to get a better understanding of the neural physiology that is intrinsic to understanding perceptual learning. This research goes beyond our epiphenomenological viewpoint, and appreciates the computations require for such decision-making tasks. Through this paper, I hope to bridge some of the disparities between existing cognitive models and circuitry models by reviewing some of foremost literature in this field. Current research has proven that neuron in the posterior parietal cortex (PPC) are essential for understanding the computations for motor-visual task, since it is a relay station for visuomotor processing. With optigenetic manipulation and neuron recordings, these articles provide the groundwork for studying neural computation of multi-sensory integration and decision making.

As an overview of some of the literature I will present, I am going to briefly describe some of the iconic studies in understanding PPC, before diving into a more in depth analysis. An

optimal percept will take into account reliability of the cues as well as the weighting of each cue to learn how to account for perceptual information in a statistically optimal manner. Fitting activity to a model may help researchers recognize their idiosyncratic response to tasks. For Churchland's experiment, she uses a novel paradigm that yields experimental findings that integrate both a multi-sensory and decision-making circuits in play in a rodent model. In a "behavior box" the rat responds to the frequency of visual flashes and/or auditory clicks, if the rat choose correctly they are rewarded accordingly; the catch is her novel method of the disruption paradigm in which changing order of the sequence changed the behavior. This disruption effected visual decisions much more than auditory ones. The role of these stability of neural representations of learned task parameters is supported by studies that show PPC is essential during category learning and can interpret new sensory stimuli for model prediction. The PPC may also be getting input from other circuits and may influence time-scaled tasks that involve redundant firing for memory. The role of the circuit thus must be flexible enough to learn in an optimal fashion but also be able to adapt to changing tasks. It's essential to understand the anatomy and physiology underlying that circuitry in order to better define the role of PPC in these tasks. The ultimate goal of this analysis is to connect our current understanding of PPC physiology with a valid computational model.

It's important to consider differences for rodent and human systems for PPC circuitry- these are not direct homologues of each other. In humans, the posterior parietal lobe consists of Brodmann areas 5 (superior parietal lobule and part of the postcentral gyrus), 7 (medial and lateral walls of the parietal cortex), 39 (angular gyrus) and 40 (supramarginal gyrus), and

contains a larger volume per area than it does in other species. Also links between high neuronal activity of human PPC and intelligence have been substantiated by recent research exploring attention (decision-making) in multi-sensory circuits. The parietal associative area (PTLp) commonly used as analogous structure to the primate PPC (Whitlock et al., 2008). The rodent PPC (rPPC) projects to three associational thalamic nuclei, the laterodorsal, lateral posterior, and the posterior nuclei. The rPPC is situated between visual and somatosensory cortices, it can be defined by its connectivity patterns or specific anatomical markers (such as distance from bregma). For measuring the rPPC many researchers use the nearby retinotopic area AM as a landmark (VISam), since AM has reliable retinotopic sign maps (Garrett et al., 2014). Many researchers disagree about if rPPC is restricted to area VISa. Wang et al., 2011 defines retinotopic areas RL, A, AM, as parts of PPC by definition. Including AM can cause issues in studying rPPC since it doesn't participate in reweighing in the same way that other areas do. Other connectivity studies define PTLp and VISam as entirely separate structures. Anatomy and connectivity studies use the term PTLp whereas functional literature preferentially uses the term PPC, however in this paper I will use the term PPC to mean how we study as comparable to primate models. One other potential problem with studying the rat PCC comes from the lack of disambiguation about organization of thalamic-cortical connections and the conflicting information about how thalamic projection- thus it is not entirely clear how isolate PPC in the rat. The ambiguous definition of PPC makes it even harder to define the subunits which may have different functionalities depending on their inputs and location. The rodent PPC is a highly interconnected structure that involves both whisker sensory and motor cortices- thus in whisker-based tactile exploration it will envelop PPC to the S1 and M1 circuitries. rPCC projections to

the secondary and primary areas of the medial somatomotor subnetwork suggest the potential role of rPPC in the conversion of sensory information to motor commands. There is still debate over whether PPC is just a relay station for computations, motor and sensory information or if it performs computations on its own.

The PPC is a hub of sensorimotor inputs and information- the PPC function after completing the learning phase of tactile decision making is to reinforce the learned circuit and adapt new behaviors if needed. The PPC is pertinent in hand-reaching behavior in monkeys and thus it is unsurprising that it plays such a critical role in active whisking for rats- proving that it consistently interplays tactile goal-directed learning and tactile calculations. The PPC is also important in memory-guided spatial navigation which may lend to it's abilities to be influenced by other circuits. It is essential to consider this when discussing how to integrate simple circuitry models surrounding PPC into our understanding complex, flexible behaviors such as decision making.

The PPC involves both neurons which are sensitive to modality-specific stimuli and others that are multimodal- these can respond to auditory, visual, somatosensory stimuli, or multi-sensory cues that weigh each modality. The PPC may not participate in direct somatosensation- rather it is part of processing of learning variable sensory features. One demonstration of this is the retinotopic areas are part of PPC preferentially respond to fast moving objects (Gao et al., 2006), and unimodal neurons are somewhat randomly appropriated between borders of the neighboring V1 and S1. Many cross-modal components in PPC of mice

have been demonstrate using learning multimodal contingencies rather than decision-making. It is unclear whether automating responses to multimodal contingencies or decision-making with multi-sensory integration. Experiments with novel stimuli versus shows that it may be in response to decision-making, since it will respond with a bias towards both and be strongly reinforced for the adapted stimuli (Mohan et al., 2018).

This confers that the primary role of PPC in learning to differentiate these exigencies from the environment, and responds to adapt to new stimuli. After learning a tactile discrimination task which began with an auditory cue, the mouse PPC presented these touch-sensitive neurons (expecting a touch cue following the sound) that responded just when auditory cue was present- this supported the possible predictive role of PPC (Mohan et al., 2018). A different task proved the capabilities of PPC in weighing sensory inputs from stimuli that evoked multiple modalities. Mice given a unimodal task- either visual and auditory, then given a mixed modality audio-visual training with conflicting cues- mastery of this task in the non-ontogenetically manipulated group showed that PPC was causally involved in this preferential weighting (Song et al., 2017). Using mice that wore goggles with prisms, they found inhibition of the visual cortex and when rPPC stopped relaying signals (blocked out signals with muscimol), there was no longer optimal response- no inhibition of the visual cortex (Yoshitake et al., 2013). This finding suggests that PPC is an area that re-weights sensory cues and is able send signals to adapt new response to the stimuli. Visual decision-making in primates use noisy visual stimuli (like a random dot motion pattern) to test the cue integration for planning. Another study (Olcese et al., 2013), cited in Yoshitake, found that rPPC can modulate the responses of

pyramidal neurons to multimodal stimuli differently than unimodal stimuli- suggesting an important role of PPC in controlling how multisensory information is processed. The PPC population activity evokes sequence of patterns during decision-making- this holds the pattern in memory for learning until conflicting sensory may disrupt the activation pattern. Unique sequence activations PPC learn cue compatibility and learned multi-sensory integration.

In a another study (Hanks et al., 2015) the duty of accumulation of learned stimuli representation was differentiated from gradual ramping of potentials versus sequential activation. Sequential activation plays a role in decision-making, especially in navigation tasks. The PPC helps to advance behaviors that are based on learned memories - thus it can change the weight of a stimuli across a learning period. The PCC holds biases from previous trials in order to inform perceptual decision- however when activating inhibitory neurons between each trial, according to Hwang et al., 2017, these biases are reduced. This may not have applied to contraction bias- an ability to represent a stimuli through working memory- in the same study aforementioned, loudness of two sounds presented with a delay, inactivation of PPC reduced the influence of sensory history on the choice. In the same study, inhibition of PPC had negligible effect on history-dependent behavior for a habituated stimuli, but during the auditory classification task an unfamiliar stimulus biased the result based upon decision-making in previous trials. Other studies have found that visually selective neurons are active only during task engagement (Olcese et al., 2013), and that these respond much more vivaciously to visual stimuli than to other modes of stimulation. However there is conflicting evidence for how rPPC neurons

may be effected in multi sensory tasks that include spatial memory. This will be elaborated upon later in the paper, first I will explain more about how memory is tested in the rPPC.

The exact role of the computations performed by PPC are still largely unknown. Inhibiting PPC while the cue is presented, and not during the delays in experiments, hinder visual and visuospatial task performance- perhaps suggesting that PPC accumulates evidence during stimulus presentation in order to make decision. Tests with new versus trained stimuli show that a delay period inhibition of PPC will still allow a bias for novel visual decisions (Zhong et al., 2018). There are often two types of delay period tests- implicit and explicit. Implicit test includes measures like the T-maze navigation that may test the perceived distance of a stimuli from cues. An explicit test, in most studies I've looked at, measures waterspout licking (something that may be hard for mice to inhibit) as a response to frequency or another type of stimuli. Tests often show that delay period inhibition has a strong effect on choice- inhibiting rPPC during a delay period may reduce the bias for a novel stimuli more than inhibiting it during stimuli presentation (Zhong et al., 2018). This may support that evidence accumulation may not processed just with PPC. Perhaps decision-making could be mediated by superior colliculus when the PPC is inhibited or with higher-order projections that reach important, decisive cortical regions. The essence of PPC's computation is based in delay-period decision-making for modality-specific- but mechanisms of PPC in these tasks are not fully conclusive. PPC implements planing as shown with memory, accumulation of sensory information, motor preparation in response to stimuli. There are clear correlates of this in human subjects- with the PPC's role in gaze focus as shown with cases of optic ataxia and hemispatial neglect.

Cognitive science and psychology have studied optimal multisensory integration through studying strategic behaviors that use sensory cue reliability, contextual cues, auditory, visual, tactile information. By bringing cognitive approaches into studies with animal models and combining theory with experimental results, recent experiments offer crucial insights into the neural mechanisms that support this ability for decision making circuits. This will provide a more thorough investigation into how translating behavioral paradigms (in animal models) and theoretical templates may elucidate neural mechanisms perceptual decision making and multisensory integration. There are clearly analogous examples in human, for example we may pay closer attention to visual cues from a person's face when we are uncertain about auditory signals (the McGurk Effect). "Even though visual and auditory stimuli don't come in exactly at the same time, we think that the brain keeps events in sequence by processing each sensory cue in parallel, fusing the two signals at a later stage and then making a judgment about the fused signal," Churchland explains in her earlier research (in an interview found online).

In Churchland's early work on multi-sensory integration, she found that rodents perform better when they get both the auditory and the visual stimuli together. In the construct of the PPC circuitry, as far as observations can predict, focused connectivity from excitatory and inhibitory neurons involve continual activation as well as rivalry for sensorimotor decision-making. Experimental data in Churchland's studies has shown that steering the neural activity in mice that had learned sensorimotor tasks (based upon auditory and visual stimuli), activates neural structures superimposed on circuits that control cortex-wide activity during decision-making.



Neural activity was measured in transgenic mice (optogenetically manipulated) that express calcium indicators in cortical excitatory neurons. Red fluorescent light exhibits differentially from green fluorescence, so that they can distinguish excitatory versus inhibitory neurons, thus evaluating their respective roles in decision-making. Computational based approaches, like classifiers and decision-making models, were used to discern neural encodings seen in their recordings and translate that activity to information necessary in decision-making computations.

Churchland's uniqueness in her experiments was her ability to create sensory confusion (disruption paradigm) for rats that required them to engaged in purposive decision-making cognitions. Churchland measured electrophysiological responses of cortical neurons in rodents as they perform the task in order to understand the neural mechanism involved. Methods such as 2-photon microscopy had distinguished the role of single neurons for the computations necessary for decision making- allowing Churchland's team to test from groups of individual neurons that have different properties in PPC. By training the mice to discriminate frequencies of flashing light and they found that the animals employed important decision-making strategies analogous to those seen in primates. In the behavior box aforementioned, this series of click and visual sequences has a disrupted pattern to ensure that the new behavior is learned from visual and auditory stimuli not just temporal/patterned cues.

This experimental approach allows the discovery of new possible regions that activate during a auditory, visual or multisensory decision-making. Also, optogenetic suppression of these areas were used to evaluate their causal role in decision-making. The model-based comparison of behavior onto the suppression of signals helps to better gauge the actual role of disruption may

effect decision-making action and percepts. Regions that are causally related to decision computations were analyzed on the level of single neurons instead of population measures.

The results of this experiment help discern how to model decision-making and Churchland's studies set the groundwork for future research on multi-sensory decision making in the PPC. This experiment also had surprisingly proven that inhibitory neurons were as selective for choice as excitatory neurons. In fact inhibitory neurons may relay information inherent in preference excitatory signals from these learned circuits. By selecting out some subnetworks of this system, the role of learning is clear with decision-making circuits reactively re-firing in response to learned stimuli.

In posterior parietal cortex, population activity changes with more information even when the animal's movements may not change correspondingly. Other studies have also suggested PPC responses are not just sensory or motor, rather they compute learned perception to action modules. Cell-specific recording methods showed strong activity between inhibitory neurons (especially those with similar stimulus selectivity). Strong inhibitory coupling was clearly observed in other contemporary paper, in primary visual cortex (V1) of passively viewing mice, and in this study PPC of mice making perceptual decisions. However the role of the PPC circuit is not entirely clear for this a simple computation for decision-making tasks- it may involve more than was previously expected.

A surge of recent research have explored the role of posterior parietal cortex (PPC) on perceptual decisions. Primarily, a recent study by Katz and colleagues shook things up with their new data demonstrating that pharmacological inactivation of primate PPC has little effect on perceptual decisions. This paper argued that despite strong modulation during perceptual decisions, primate PPC is not a member of the causal circuit for visual motion decisions. This data has been contested by other researcher that provide conflicting evidence. Other papers about rodent PPC, presents a contrary view- this isn't unexpected, since although rodent and primate PPC are similar, they have a number of anatomical and functional differences as I had mentioned earlier in the paper.

In a recent paper by Goard, mouse PPC neurons were studied during a visual detection task. The paper attempted to explain the interplay between role of visual (V1), posterior parietal (PPC), and frontal motor (fMC) through a memory-guided visual discrimination task. In this paradigm head-fixed mice were trained to distinguish between two visual stimuli, one signaling to lick the spout for water, and then the other signaling to withhold licking. This experiment included head-fixation this it allowed for a better optical recording and manipulation of neural activity during the course of a trial. This experimental design included a paradigm in which the mice were shown a horizontal or vertical grating and after a 3-9 second delay the mice responded to the vertical grating by licking a spout. The authors disrupted rPPC activity via an optogenetic manipulation in order to test the effects of “cutting off” that circuitry. They found that performance declined considerably when the activation took place during the time the grating was visible to the mice. The fMC was very active during delay and response, perhaps suggesting

that choice in memory is held in fMC and other areas may play a greater role during transformation period. Surprisingly the rPPC neurons activated at times during other parts of the trial such as during the delay and movement periods, the disruption paradigm proved to have little consequence on performance at those times. This argues that the activity during those periods may reflect signals that are computed elsewhere and fed back to PPC or that learning other actions will stir up activity in PPC. During the transformation period the exact computations of the PPC are unknown in this experiment but it is posited in later papers that it may play a role in accumulating evidence for memory decisions.

In Krumin's paper showed that sequential coding in the rPCC model is not driven by choice- rather it is processed with trajectory and heading information as the mouse participates in the task. Sequential coding for manipulating decision-making and choice paradigms in PPC is a popular method, but it may be specific to navigation tasks. Like in the Goard paper, another paper (Harvey et.al, 2018) had investigated whether rPPC neurons prefer purely sensory detection or are invested in planning based on sensory information. In following studies- decision-making was studied differently than how Churchland had set up the paradigm; the rat runs through a T-maze in a virtual reality and after observing the cue – a tower on either side of the maze – the animal runs toward the crossing point in the maze at which it decides, without further cues, which way to go to get the reward. In this study population code similar to the one observed in other studies can be explained by location and heading tuning of rPPC neurons. The activity of rPPC neurons has been implicated in encoding movements before they occur and planning movements given sensory information. In other studies (Funamizu et al., 2016)

perceived position of the sound source became closer to the animal as the animal had ran with it's head fixed on a treadmill. Brief silence periods provides a delay in which the mouse engaged in a memory-guided sensory decision in which it chose based upon it's memory of localizing the sound. This was an interesting twist to the experiment because unlike in the Goard paper the mouse had made an implicit decision to chose direct instead of explicitly responding of the go or no go task. The role of rPPC in predictive coding was clear though their manipulation- inactivation of rPPC correlated to the rat's inability to consistently update their prediction of running distance whenever the sensory information was not present at that time. Through learning the properties of sensory information in the rat's environment in this study, the rPPC was shown to manipulate and regulate neural responses in the upstream areas.

In another paper by Churchland, she found that computations may occur inside the rPPC may be important for immediate perceptual decision not just memory-based tasks- concurring with data in Funamizu study. Churchland's study models how the rPPC is accumulating evidence for decision alternatives and made clear its causal role in decision making paradigms. Like the Goard paper, they found that performance declined when we stimulated while animals were facing visual stimuli for decision-making task. This mainly tested the period in which the rat was presented with the stimuli thus it cannot directly be correlated with the results with disruption at other times. Churchland did, however, compare disruption on visual vs. auditory trials in the same animal and the same session, and found that effects were mostly restricted to visual decisions. This concurs some with the information found in the Goard experiment

aforementioned but overlay the decision component of rPPC neurons, and also with deficits on a visual memory task reported in mice by Harvey and Tank.

In their research, Harvey and Tank take a more computational model-based approach. They attempt to show how unstructured networks can sometimes be better at learning task than more rigidly built network. These unstructured networks can produce structured outputs on slow timescales. Slow timescales are pertinent to the study of decision-making, since it includes facets of cognitive processes like working memory- which persists on slower timescales. Perceptual driven tasks, that include multi sensory integration require these network to reinforce sensorimotor responses with redundant firing. The PPC contains individual neurons that are able to encode for learned information over delays- keeping the information from the previous readily available in case they animals needs to make an ambiguous decision or encode new information. In a mouse PPC, memory guided decision task resulted in many individual neurons respond reflexively- in less than the amount of time of it takes for the rodent to be aware of these memories and learning. It is posited that these neurons fire sequentially in response to the stimuli- thus supporting slow-timescale memory-guided decisions and that these computation don't require redundant firing for memories. Harvey and Tank revealed in their paper that a randomly connected network can guide slow-timescale, memory-guided decisions computations. As part of their work they developed new infrastructure called PINning- which uses FORCE learning to mimic coherent activity patterns in these chaotic networks that they've modeled. There are a few key difference in this model. Firstly, in the PINing model just ~12% of synaptic weights can be reevaluated in this group of 437 neurons that imitates their

understanding of the network dynamics for PPC neurons. This paper also included interesting facets to its model- like bump attractors. Bump attractors are popular for modeling persistent activity- these bumps do not decay and are able to represent encoding salience of a stimuli. In the network bump attractors can be seen as a rise in activity (bump) that progresses across the network- playing a key role in later persistent responses. Their study found that the network was mostly driven by strongly choice-selective neurons. However, the non-selective neurons played a major modulatory role in this model- “conveyer belt” that allowed for evidence accumulation and kept decision alternatives in mind.

The putative mechanisms for working memory and decision-making for circuits in PCC are still largely unknown and complex beyond what current research has comprehended. In the models and experiments discussed, some causal manipulations provide compelling evidence that PPC is involved in perceptual biases. Models of single neuron persistence show that persistent firing may allow for stimulus representation in memory and it's stability can directly measure the strength of learning in a task. The PCC may be essential for such biases and updates- but with the idea of the unstructured network, it can be concluded that there must be enough strength to hold memory but enough flexibility to update to new alternatives.

Through this discussion, I hope that we can look at recent literature with a critical lens. PPC is a multisensory associative area that has played a crucial part in sensory decision-making. Although there are notable discrepancies in the literature, it most likely responds to the diverse responses and properties that such an integral relay station like PPC can play. The mouse PPC

has provided a useful model system for a circuit-level understanding but it may not directly relate to how primate PPC functions and may influence our models towards incorporating information that cannot be generalized (such as biases from different haptics, with whisker sensory systems).

Although the neuron's specific contributions to decision-making may still be unknown, but Churchland and other researchers have offered fresh insights into how to better test predictions of long-standing models of decision-making. It is clear through these studies that learning shapes the activity of these circuits. Further studies and reviews are needed to discern the exact mechanisms and to understand the role of outside circuits that may provide feedback, changing PPC neural encodings.

## **Citations:**

***1. Najafi, F., Elsayed, G.F., Cao, R., Pnevmatikakis, E., Latham, P.E., Cunningham, J.P., and Churchland, A.K. (2018). Excitatory and inhibitory subnetworks are equally selective during decision-making and emerge simultaneously during learning. bioRxiv. <https://doi.org/10.1101/354340>.***

***2. Katz, L.N., Yates, J.L., Pillow, J.W., and Huk, A.C. (2016). Dissociated functional significance of decision-related activity in the primate dorsal stream. Nature 535, 285–288***

***3. Posterior parietal cortex guides visual decisions in rats  
Angela M. Licata, Matthew T. Kaufman, David Raposo, Michael B. Ryan, John P. Sheppard, Anne K. Churchland  
bioRxiv 066639; doi: <https://doi.org/10.1101/066639>  
Now published in The Journal of Neuroscience doi: 10.1523/JNEUROSCI.0105-17.2017***



4. Harvey, Christopher D., Tank, David W. Choice-specific sequences in parietal cortex during a virtual-navigation decision task. *Nature*. 2012/03/14/online doi: <https://doi.org/10.1038/nature10918>

5. *Multisensory Decision-Making in Rats and Humans*

David Raposo, John P. Sheppard, Paul R. Schrater, Anne K. Churchland

*Journal of Neuroscience* 14 March 2012, 32 (11) 3726-3735; DOI:10.1523/JNEUROSCI.4998-11.2012

6. Goard, M. J., Pho, G. N., Woodson, J., & Sur, M. (2016). Distinct roles of visual, parietal, and frontal motor cortices in memory-guided sensorimotor decisions. *Elife*, 5, e13764.

7. Krumin, M., Lee, J. J., Harris, K. D., & Carandini, M. (2018). Decision and navigation in mouse parietal cortex. *Elife*, 7, e42583.

8. C.D. Harvey, P. Coen, D.W. Tank. Choice-specific sequences in parietal cortex during a virtual-navigation decision task. *Nature*, 484 (2012), pp. 62-68, 10.1038/nature10918.

9. A. Funamizu, B. Kuhn, K. Doya. Neural substrate of dynamic Bayesian inference in the cerebral cortex. *Nat. Neurosci.*, 19 (2016), pp. 1682-1689, 10.1038/nn.4390.

10. E.J. Hwang, J.E. Dahlen, M. Mukundan, T. Komiyama. History-based action selection bias in posterior parietal cortex. *Nat. Commun.*, 8 (2017), p. 1242, 10.1038/s41467-017-01356-z.

11. E. Gao, C. DeAngelis, A. Burkhalter. Specialized areas for shape and motion analysis in mouse visual cortex. *Soc. Neurosci. Abstr.* (2006), p. 32

12. H. Mohan, Y. GalleroSalas, S. Carta, J. Sacramento, B. Laurenczy, L.T. Sumanovski, C.P.J. De Kock, F. Helmchen, S. Sachidhanandam. Sensory representation of an auditory cued tactile stimulus in the posterior parietal cortex of the mouse. *Sci. Rep.*, 8 (2018), pp. 1-13, 10.1038/s41598-018-25891-x

11. Y.H. Song, J.H. Kim, H.W. Jeong, I. Choi, D. Jeong, K. Kim, S.H. Lee. A neural circuit for auditory dominance over visual perception. *Neuron*, 93 (2017), pp. 940-954, 10.1016/j.neuron.2017.01.006

12. K. Yoshitake, H. Tsukano, M. Tohmi, S. Komagata, R. Hishida, T. Yagi, K. Shibuki. Visual map shifts based on whisker-guided cues in the young mouse visual cortex. *Cell Rep.*, 5 (2013), pp. 1365-1374, 10.1016/j.celrep.2013.11.006

13. U. Olcese, G. Iurilli, P. Medini. Cellular and synaptic architecture of multisensory integration in the mouse neocortex. *Neuron*, 79 (2013), pp. 579-593, 10.1016/j.neuron.2013.06.010