

CAS CN740: Topics in Sensory-Motor Control

Spring 2008 Syllabus

INSTRUCTOR:

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REQUIRED TEXTS:

Kandel, E., Schwartz, J.H., and Jessell, T.M. (2000). *Principles of Neural Science*, 4th Edition.
New York: McGraw-Hill.

OTHER USEFUL TEXTS:

Kent, R. D., Atal, B. S., and Miller, J. L. (1991) *Papers in Speech Communication: Speech Production*. Woodbury, NY: Acoustical Society of America.

Levelt, W. (1989). *Speaking: From Intention to Articulation*. Cambridge, MA: MIT Press.

Paillard, J. (1991). *Brain and Space*. Oxford: Oxford University Press.

COURSE OVERVIEW:

CN740 addresses topics in neural modeling of sensory-motor control not currently covered in depth in CN540 or CN560. The course is broken roughly into two sections, dealing with two important areas of sensory-motor control research: (1) spatial representation for movement planning and (2) speech production. Attention is paid to relevant psychophysical data and neural models in these areas. The unifying theme of the course concerns the identification of appropriate levels of representation and interactions between these levels for the study and modeling of different sensory-motor tasks.

There are three major assignments for this course, all designed around a course project. First, each student is required to prepare a 50-minute in-class presentation surveying the research literature relevant to their chosen project and lead a subsequent 30-minute class discussion (see p. 3). Students are also required to write a project report and give a short in-class presentation of the final project, both due on the last day of class. A typical project will consist of a literature review and either a modeling effort or an experiment. Alternatively, a more thorough literature review can be combined with a sketchier description of a modeling project. Students should set up an appointment with me to discuss their project ideas by no later than Feb. 10.

GRADING CRITERIA:

Literature review presentation:	35 %
Project report:	50 %
Final project presentation:	15 %

LITERATURE REVIEW PRESENTATIONS:

During weeks 6-8 of the course, each student will be required to present a 50-minute lecture and lead a subsequent 30-minute discussion on the research area they choose for their projects. You should choose your project topic and have it approved by me as soon as possible, but definitely no later than week 4. The goals of this assignment are: (1) to insure that students get an early start on their projects, (2) to insure that the projects include adequate treatments of the current status of the field, (3) to provide a forum for getting the opinions of others before writing up the bulk of the project, (4) to provide the class with material from viewpoints different from my own, and (5) to provide students with an opportunity to give a presentation of “job talk” length.

Presentations will be graded on how well they adhere to the following guidelines:

- Make the lecture simple and clear enough that someone with no prior knowledge of the field can follow it. This is important not only for insuring a useful lecture but also for maximizing the utility of the discussion period. By far the most common mistakes made by people preparing their first presentations are assuming too much audience knowledge and trying to cover too much material.
- Practice the lecture to make sure it is not too long, keeping in mind that there might be a few questions during the lecture. A length of about 50-55 minutes with no interruptions should be about right.
- Try to avoid putting too much text on slides. Descriptions revolving around a diagram are usually easier to follow than lengthy verbal treatments.
- It is often useful to provide an outline of the talk at the beginning and refer to it at several stages during the talk. This helps insure that audience members keep track of the “big picture” even if they get lost and zone out during some of the details.
- Use a large font (18pt or larger) for lecture slides.
- Make copies of typed lecture slides for all members of the class. Lecture note copies can be made on the department copying machine. If possible, print the notes with two or four slides per page.
- Prepare a list of 5 to 10 discussion questions to be addressed by the class, ordered by importance. Ideally, these should be questions you still have after your reading of the literature so the class discussion can help you hone your ideas for the project. The presenter will be responsible for insuring that the discussion progresses smoothly.
- If carefully prepared, the presentation outline often serves as an excellent basis for the expository structure of a subsequent article, or, in this case, project writeup. Therefore, try to present the material as a coherent “story” that serves as the underlying structure of your talk. I find it useful to pose key questions that one might have when addressing a particular research area, then compare and contrast the different answers to these questions found in the literature.
- To avoid an overemphasis on public speaking skills, presentation grades will primarily be based on how well the presenter has *prepared* for the lecture and discussion.

SESSION 1 (January 22)

Overview of biological spatial representation. Different types of representations for different motor tasks. Anatomy and physiology of spatial representation.

Required readings:

- Gardner, E.P., & Martin, J.H. (2000). Coding of sensory information. *Principles of Neural Science*, Chapter 21.
- Gardner, E.P., Martin, J.H., Jessell, T.M. (2000). The bodily senses. *Principles of Neural Science*, Chapter 22.
- Gardner, E.P., & Kandel, E.R. (2000). Touch. *Principles of Neural Science*, Chapter 23.
- Pearson, K. & Gordon, J. (2000). Spinal reflexes. *Principles of Neural Science*, Chapter 36.
- Rizzolatti, G., Luppino, G., and Matelli, M. (1998). The organization of the cortical motor system: New concepts. *Electoencephalography and Clinical Neurophysiology*, **196**, pp. 283-296.

Supplemental readings:

- Olson, C.R. and Hanson, S.J. (1990). Spatial representation of the body. In Hanson, S.J. and Olson, C.R., (eds.): *Connectionist Modeling and Brain Function*, ch. 8, pp. 193-254. Cambridge, MA: MIT Press.
- Saltzman, E. (1979). Levels of sensorimotor representation. *Journal of Mathematical Psychology*, **20**, pp. 91-163.
- Matthews, P.B.C. (1964). Muscle spindles and their motor control. *Physiological Reviews*, **4**, pp. 219-288.
- Stein, J.F. (1989). Representation of egocentric space in the posterior parietal cortex. *The Quarterly Journal of Experimental Physiology*, **74**, pp. 583-606.
- Stein, J.F. (1991). Space and the parietal association areas. In Paillard, J., (ed.): *Brain and Space*, ch. 11, pp. 185-222. Oxford: Oxford University Press.
- Stein, J.F. (1992). The representation of egocentric space in the posterior parietal cortex. *Behavioral and Brain Sciences*, **15**(4), pp. 691-700.
- Fogassi, L., Gallese, V., diPellegrino, G., Fadiga, L., Gentilucci, M., Luppino, G., Matelli, M., Pedotti, A., and Rizzolatti, G. (1992). Space coding by premotor cortex. *Experimental Brain Research*, **89**, pp. 686-690.

SESSION 2 (January 29)

Models of body-centered spatial representation. The representation of space in the motor cortex: 3-D interpretations vs. joint space interpretations in recent models of motor cortical function.

Required readings:

- Krakauer, J. and Ghez, C. (2000). Voluntary Movement. *Principles of Neural Science*, Chapter 38.
- Guenther, F.H., Bullock, D., Greve, D., and Grossberg, S. (1994). Neural representations for sensory-motor control, III: Learning a body-centered representation of 3-d target position. *Journal of Cognitive Neuroscience*, **6**(4), pp. 341-358.

Supplemental readings:

- Andersen, R.A. and Zipser, D. (1988). The role of the posterior parietal cortex in coordinate transformations for visual-motor integration. *Canadian Journal of Physiology and Pharmacology*, **66**, pp. 488-501.
- Zipser, D. and Andersen, R.A. (1988). A back-propagation programmed network that simulates response properties of a subset of posterior parietal neurons. *Nature*, **331**, pp. 679-684.
- Greve, D., Grossberg, S., Guenther, F.H., and Bullock, D. (1993). Neural representations for sensory-motor control, I: Head-centered 3-D target positions from opponent eye commands. *Acta Psychologica*, **82**, pp. 115-138.
- Grossberg, S., Guenther, F.H., Bullock, D., and Greve, D. (1993). Neural representations for sensory-motor control II: Learning a head-centered visuomotor representation of 3-D target positions. *Neural Networks*, **6**, pp. 43-67.
- Flanders, M., Helms Tillery, S.I., and Soechting, J.F. (1992). Early stages in a sensorimotor transformation. *Behavioral and Brain Sciences*, **15**, pp. 309-362.
- Morasso, P. (1981). Spatial control of arm movements. *Experimental Brain Research*, **42**, pp. 223-227.
- Georgopoulos, A.P., Kalaska, J.F., Caminiti, R., and Massey, J.T. (1982). On the relations between the direction of two-dimensional arm movements and cell discharge in primate motor cortex. *Journal of Neuroscience*, **2**, pp. 1527-1537.
- Georgopoulos, A.P., Kalaska, J.F., Crutcher, M.D., Caminiti, R., and Massey, J.T. (1984). The representation of movement direction in the motor cortex: Single cell and population studies. In Edelman, G.M., Gall, W.E., and Cowan, W.M., (eds.): *Dynamic Aspects of Neocortical Function*, pp. 501-524. New York: Wiley.
- Georgopoulos, A.P., Kettner, R.E., and Schwartz, A.B. (1988). Primate motor cortex and free arm movements to visual targets in three-dimensional space. II. Coding of the direction of movement by a neuronal population. *Journal of Neuroscience*, **8**(8), pp. 2928-2937.
- Georgopoulos, A.P., Lurito, J.T., Petrides, M., Schwartz, A.B., and Massey, J.T. (1989). Mental rotation of the neuronal population vector. *Science*, **243**, pp. 234-236.

- Kettner, R.E., Schwartz, A.B., and Georgopoulos, A.P. (1988). Primate motor cortex and free arm movements to visual targets in three-dimensional space. III. Positional gradients and population coding of movement direction from various movement origins. *Journal of Neuroscience*, **8**(8), pp. 2938-2947.
- Schwartz, A.B., Kettner, R.E., and Georgopoulos, A.P. (1988). Primate motor cortex and free arm movements to visual targets in three-dimensional space. I. Relations between single cell discharge and direction of movement. *Journal of Neuroscience*, **8**(8), pp. 2913-2927.
- Kalaska, J.F., Cohen, D. A.D., Hyde, M.L., and Prud'homme, M. (1989). A comparison of movement direction-related versus load direction-related activity in primate cortex, using a two-dimensional reaching task. *Journal of Neuroscience*, **9**(6), pp. 2080-2102.
- Kalaska, J.F. and Crammond, D.J. (1992). Cerebral cortical mechanisms of reaching movements. *Science*, **255**, pp. 1517-1523.

SESSION 3 (February 5)

Transforming spatial plans into motor actions (inverse kinematics), and how this transformation relates to the spatial form of reaching movements and cell properties in motor cortex.

Required readings:

- Mussa-Ivaldi, F.A. (1988). Do neurons in the motor cortex encode movement direction? An alternative hypothesis. *Neuroscience Letters*, **91**, pp. 106-111.
- Guenther, F.H., and Micci Barreca, D. (1997). Neural models for flexible control of redundant systems. In: P. Morasso and V. Sanguineti (eds.), *Self-organization, Computational Maps, and Motor Control* (pp. 383-421). Amsterdam: Elsevier-North Holland.
- Scott, S.H., Gribble, P.L., Graham, K.M., and Cabel, D.W. (2001). Dissociation between hand motion and population vectors from neural activity in motor cortex. *Nature*, **413**, pp. 161-165.

Supplemental readings:

- Bullock, D., Grossberg, S., and Guenther, F.H. (1993). A self-organizing neural model of motor equivalent reaching and tool use by a multijoint arm. *Journal of Cognitive Neuroscience*, **5**, pp. 408-435.
- Burnod, Y., Grandguillaume, P., Otto, I., Ferraina, S., Johnson, P.B., and Caminiti, R. (1992). Visuomotor transformations underlying arm movements toward visual targets: A neural network model of cerebral cortical operations. *Journal of Neuroscience*, **2**(4), pp. 1435-1453.
- Caminiti, R., Johnson, P., and Urbano, A. (1990). Making arm movements within different parts of space: Dynamic aspects in the primate motor cortex. *Journal of Neuroscience*, **10**, pp. 2039-2058.
- Alexander, G.E. and Crutcher, M.D. (1990). Neural representations of the target (goal) of visually guided arm movements in three motor areas of the monkey. *Journal of Neurophysiology*, **64**(1), pp. 164-178.

SESSION 4 (February 12) – Guest lecture by Dr. Anatoli Gortchetchnikov

Spatial representation in the hippocampus.

Required readings:

- Muller, R.U., Kubie, J.L., Bostock, E.M., Taube, J.S., and Quirk, G.J. (1991). Spatial firing correlates of neurons in the hippocampal formation of freely moving rats. In Paillard, J., (ed.): *Brain and Space*, pp. 296-333. Oxford: Oxford University Press.
- McNaughton, B.L., Chen, L.L., and Markus, E.J. (1991). "Dead reckoning", landmark learning, and the sense of direction: A neurophysiological and computational hypothesis. *Journal of Cognitive Neuroscience*, **3**(2), pp. 190-202.

Supplemental readings:

- Muller, R.U. and Kubie, J.L. (1987). The effects of changes in the environment on the spatial firing of hippocampal complex-spike cells. *Journal of Neuroscience*, **7**(7), pp. 1951-1968.
- Muller, R.U., Kubie, J.L., and Ranck, J.B. (1987). Spatial firing patterns of hippocampal complex-spike cells in a fixed environment. *Journal of Neuroscience*, **7**(7), pp. 1935-1950.
- O'Keefe, J. (1988). Computations that the hippocampus might perform. In Nadel, L., Cooper, L.A., Culicover, P., and Harnish, R.M.(eds.): *Neural Connections and Mental Computations*, pp. 225-284. Cambridge, MA: MIT Press.
- O'Keefe, J. (1990). A computational theory of the hippocampal cognitive map. *Progress in Brain Research*, **83**, pp. 301-312.
- O'Keefe, J. (1991). The hippocampal cognitive map and navigational strategies. In Paillard, J. (ed.): *Brain and Space*, ch. 16, pp. 273-295. Oxford University Press.
- O'Keefe, J. and Nadel, L. (1978). *The Hippocampus as a Cognitive Map*. Oxford: Clarendon Press.
- Rolls, E.T. (1991). Functions of the primate hippocampus in spatial processing and memory. In Paillard, J. (ed.): *Brain and Space*, pp. 353-376. Oxford: Oxford University Press.
- Burgess, N., O'Keefe, J., and Recce, M. (1993). Using hippocampal 'place cells' for navigation, exploiting phase coding. In Hanson, S.J., Giles, C.L., and Cowan, J.D. (eds.): *Advances in Neural Information Processing Systems 5*, pp. 929-936. San Mateo, CA: Morgan Kaufman.
- Taub, J.S., Muller, R.U., and Ranck, J. B.J. (1990a). Head-direction cells recorded from the postsubiculum in freely moving rats. I. Description and quantitative analysis. *Journal of Neuroscience*, **10**(2), pp. 420-435.
- Taub, J.S., Muller, R.U., and Ranck, J. B.J. (1990b). Head-direction cells recorded from the postsubiculum in freely moving rats. II. Effects of environmental manipulations. *Journal of Neuroscience*, **10**(2), pp. 436-447.

SESSION 5 (February 26)

The vestibular system, posture, and perception of self-motion and object motion in allocentric space.

Required readings:

- Goldberg, M.E., and Hudspeth, A.J. (2000). The vestibular system. *Principles of Neural Science*, Chapter 40.
- Jones, G.M. (2000). Posture. *Principles of Neural Science*, Chapter 41.
- Mergner, T., Rottler, G., Kimmig, H., and Becker, W. (1992). Role of vestibular and neck inputs for the perception of object motion in space. *Experimental Brain Research*, **89**, pp. 655-668.

Supplemental readings:

- Mergner, T., Siebold, C., Schweigart, G., and Becker, W. (1991). Human perception of horizontal trunk and head rotation in space during vestibular and neck stimulation. *Experimental Brain Research*, **85**, pp. 389-404.
- Cohen, B. and Henn, V. (Eds.) (1998). *Representation of Three-Dimensional Space in the Vestibular, Oculomotor, and Visual Systems*. Volume 545 of *Annals of the New York Academy of Sciences*. New York: New York Academy of Sciences.
- Lackner, J.R. and DiZio, P. (1988). Gravitational effects on nystagmus and on perception of orientation. In Cohen, B. and Henn, V. (eds.): *Representation of Three-Dimensional Space in the Vestibular, Oculomotor, and Visual Systems*, pp. 93-104. New York: New York Academy of Sciences.
- Ezure, K. and Graf, W. (1984). A quantitative analysis of the spatial organization of the vestibulo-ocular reflexes in lateral- and frontal-eyed animals - I. Orientation of semicircular canals and extraocular muscles. *Neuroscience*, **12**, pp. 85-93.
- Blanks, R.H.I., Curthoys, I.S., Bennett, M.L., and Markham, C.H. (1985). Planar relationships of the semicircular canals in rhesus and squirrel monkeys. *Brain Research*, **340**, pp. 315-324.

SESSIONS 6-8 (March 4, March 18, March 25)

Student literature review presentations.

Required readings:

To be announced.

Supplemental readings:

To be announced.

SESSION 9 (April 1)

Overview of speech production. Infant babbling and the development of speech. Overview of the neural bases of speech and language.

Required readings:

- Dronkers, N.F., Pinker, S., and Damasio, A. (2000). Language and the aphasias. *Principles of Neural Science*, Chapter 59.
- MacNeilage, P.F. and Davis, B. (1990a). Acquisition of speech production: Frames, then content. In Jeannerod, M. (ed.): *Attention and Performance XIII: Motor Representation and Control*, pp. 453-476. Hillsdale, NJ: Erlbaum.

Supplemental readings:

- Levelt, W. (1989). *Speaking: From Intention to Articulation*, ch.11, pp. 413-457. Cambridge, MA: MIT Press.
- Daniloff, R., Schuckers, G., and Feth, L. (1980). *The Physiology of Speech and Hearing: An Introduction*, Chapters 7-8. Englewood Cliffs, NJ: Prentice Hall.
- Flanagan, J.L. (1972). *Speech Analysis and Perception*, Chapters 1-2. New York: Springer-Verlag.
- Oller, D.K. (1980). The emergence of the sounds of speech in infancy. In Yeni-Komshian, G.H., Kavanagh, J.F., and Ferguson, C.A. (eds.): *Child Phonology. Volume 1: Production*, pp. 93-112. New York: Academic Press.
- Stark, R.E. (1980). Stages of speech development in the first year of life. In Yeni-Komshian, G.H., Kavanagh, J.F., and Ferguson, C.A. (eds.): *Child Phonology. Volume 1: Production*, pp. 73-92. New York: Academic Press.
- MacNeilage, P.F. and Davis, B.L. (1990b). Acquisition of speech production: The achievement of segmental independence. In Hardcastle, W.-J. and Marchal, A. (eds.): *Speech Production and Speech Modelling*, pp. 55-68. Dordrecht: Kluwer Academic Publishers.

SESSION 10 (April 8)

Speech production/coarticulation models from 1965-1980. Look-ahead vs. coproduction models of coarticulation.

Required readings:

- Öhman, S.E.G. (1966). Coarticulation in vcv utterances: Spectrographic measurements. *Journal of the Acoustical Society of America*, **39**, pp. 151-168.
- MacNeilage, P.F. (1970). Motor control of serial ordering of speech. *Psychological Review*, **77**(3), pp. 182-196.
- Lindblom, B., Lubker, J., and Gay, T. (1979). Formant frequencies of some fixed-mandible vowels and a model of speech motor programming by predictive simulation. *Journal of Phonetics*, **7**(1), pp. 147-161.
- Boyce, S.E., Krakow, R.A., Bell-Berti, F., and Gelfer, C.E. (1990). Converging sources of evidence for dissecting articulatory movements into core gestures. *Journal of Phonetics*, **18**, pp. 173-188.

Supplemental readings:

- Kent, R.D. and Minifie, F.D. (1977). Coarticulation in recent speech production models. *Journal of Phonetics*, **5**, pp. 115-133.
- Lashley, K.S. (1951). The problem of serial order in behavior. In Jeffress, L.A. (ed.): *Cerebral Mechanisms in Behavior*, pp. 112-136. New York: John Wiley and Sons, Inc.
- Daniloff, R., Schuckers, G., and Feth, L. (1980). *The Physiology of Speech and Hearing: An Introduction*. Englewood Cliffs, NJ: Prentice Hall.
- Kozhevnikov, V.A. and Chistovich, L. (1965). *Speech: Articulation and perception*. Translation available from Joint Publications Research Service, United States Department of Commerce, Washington, D.C., No. 30,543.
- Henke, W. (1966). *Dynamic articulatory model of speech production using computer simulation*. PhD thesis, Massachusetts Institute of Technology.
- Wickelgren, W.A. (1969). Context-sensitive coding, associative memory, and serial order in (speech) behavior. *Psychological Review*, **76**, pp. 1-15.
- Perkell, J.S. (1980). Phonetic features and the physiology of speech production. In Butterworth, B. (ed.): *Language Production*, vol. 1, ch. 13, pp. 337-372. New York: Academic Press.
- Bell-Berti, F. and Harris, K.S. (1979). Anticipatory coarticulation: Some implications from a study of lip rounding. *Journal of the Acoustical Society of America*, **65**(5), pp. 1268-1270.
- Benguerel, A.P. and Cowan, H.A. (1974). Coarticulation of upper lip protrusion in French. *Phonetica*, **30**, pp. 41-55.

SESSION 11 (April 15) Guest Lecturer: Maya Peeva

The Haskins Laboratories “gestural” view of speech. Intrinsic timing and the *coordinative structure* modeling concept. The task dynamic model.

Required readings:

- Fowler, C.A. (1980). Coarticulation and theories of extrinsic timing. *Journal of Phonetics*, **8**, pp. 113-133.
- Kelso, J. A.S. and Tuller, B. (1987). Intrinsic time in speech production: Theory, methodology, and preliminary observations. In Keller, E. and Gopnik, M., (eds.): *Motor and Sensory Processes of Language*, ch. 8, pp. 203-222. Hillsdale, NJ: Erlbaum.
- Saltzman, E.L. and Munhall, K.G. (1989). A dynamical approach to gestural patterning in speech production. *Ecological Psychology*, **1**(4), pp. 333-382.

Supplemental readings:

- Browman, C.P. and Goldstein, L. (1987). Tiers in articulatory phonology, with some implications for casual speech. *Haskins Laboratories Status Report on Speech Research*, **SR-92**, pp. 1-30.
- Browman, C.P. and Goldstein, L. (1990). Gestural specification using dynamically-defined articulatory structures. *Journal of Phonetics*, **18**, pp. 299-320.
- Saltzman, E.L. and Kelso, J.A.S. (1987). Skilled actions: A task-dynamic approach. *Psychological Review*, **94**(1), pp. 84-106.
- Kelso, J. A.S., Tuller, B., Vatikiotis-Bateson, E., and Fowler, C.A. (1984). Functionally specific articulatory cooperation following jaw perturbations during speech: Evidence for coordinative structures. *Journal of Experimental Psychology: Human Perception and Performance*, **10**(6), pp. 812-832.
- Lashley, K.S. (1951). The problem of serial order in behavior. In Jeffress, L.A. (ed.): *Cerebral Mechanisms in Behavior*, pp. 112-136. New York: John Wiley and Sons, Inc.
- Folkins, J.W. and Abbs, J.H. (1975). Lip and jaw motor control during speech: Responses to resistive loading of the jaw. *Journal of Speech and Hearing Research*, **18**, pp. 207-220.
- Fowler, C.A. and Turvey, M.T. (1980). Immediate compensation in bite-block speech. *Phonetica*, **37**, pp. 306-326.
- Abbs, J.H. and Gracco, V.L. (1984). Control of complex motor gestures: Orofacial muscle responses to load perturbations of lip during speech. *Journal of Neurophysiology*, **51**(4), pp. 705-723.
- Tuller, B. and Kelso, J. A.S. (1990). Phase transitions in speech production and their perceptual consequences. In Jeannerod, M. (ed.): *Attention and Performance XIII: Motor Representation and Control*, pp. 429-452. Hillsdale, NJ: Erlbaum.

SESSION 12 (April 22)

Articulatory synthesis and the DIVA model of speech production.

Required readings:

Guenther, F.H., Ghosh, S.S., and Tourville, J.A. (2006). Neural modeling and imaging of the cortical interactions underlying syllable production. *Brain and Language*, **96**, pp. 280-301.

Supplementary readings:

Maeda, S. (1990). Compensatory articulation during speech: Evidence from the analysis and synthesis of vocal tract shapes using an articulatory model. In W.J. Hardcastle and A. Marchal (Eds.), *Speech production and speech modelling* (pp. 131-149). Boston: Kluwer Academic Publishers.

Rubin, P., Baer, T., and Mermelstein, P. (1981). An articulatory synthesizer for perceptual research. *Journal of the Acoustical Society of America*, **70**(2), pp. 321-328.

Guenther, F.H. (1995). Speech sound acquisition, coarticulation, and rate effects in a neural network model of speech production. *Psychological Review*, **102**, pp. 594-621.

Guenther, F.H., Hampson, M., and Johnson, D. (1998). A theoretical investigation of reference frames for the planning of speech movements. *Psychological Review*, **105**, pp. 611-633.

Guenther, F.H., Espy-Wilson, C.Y., Boyce, S.E., Matthies, M.L., Zandipour, M., and Perkell, J.S. (1999). Articulatory tradeoffs reduce acoustic variability during American English /t/ production. *Journal of the Acoustical Society of America*, **105**, pp. 2854-2865.

SESSION 13 (April 29)

Student final presentations.