Cognitive Media Processing #10

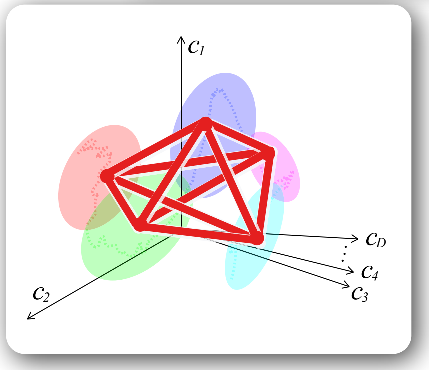
Nobuaki Minematsu

Title of each lecture

- Theme-1
  - ~~Multimedia information and humans~~
  - ~~Multimedia information and interaction between humans and machines~~
  - ~~Multimedia information used in expressive and emotional processing~~
  - ~~A wonder of sensation - synesthesia -~~

- Theme-2
  - ~~Speech communication technology - articulatory & acoustic phonetics -~~
  - ~~Speech communication technology - speech analysis -~~
  - ~~Speech communication technology - speech recognition -~~
  - ~~Speech communication technology - speech synthesis -~~

- Theme-3
  - ~~A new framework for “human-like” speech machines #1~~
  - A new framework for “human-like” speech machines #2
  - A new framework for “human-like” speech machines #3
  - A new framework for “human-like” speech machines #4



Speech is extremely variable.

- Various factors change speech acoustics easily.

- The world's tiniest high school girl

A difference bet. machines and humans

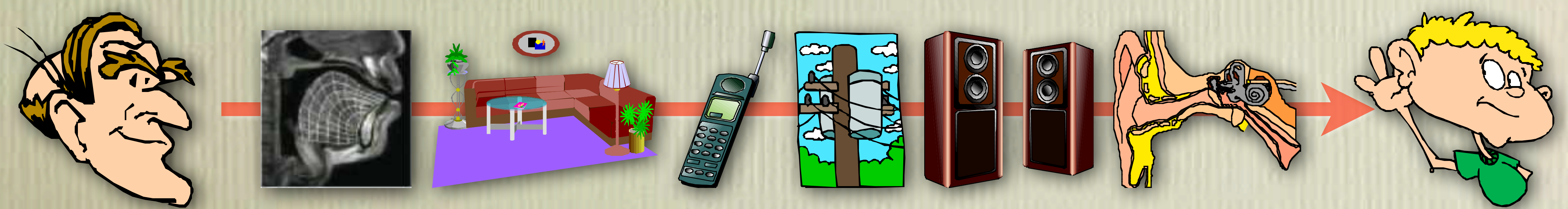
Machine strategy (engineers' strategy): ASR

- Collecting a huge amount of speaker-balanced data
  - Statistical training of acoustic models of individual phonemes (allophones)
- Adaptation of the models to new environments and speakers
  - Acoustic mismatch bet. training and testing conditions must be reduced.

?

Human strategy: HSR

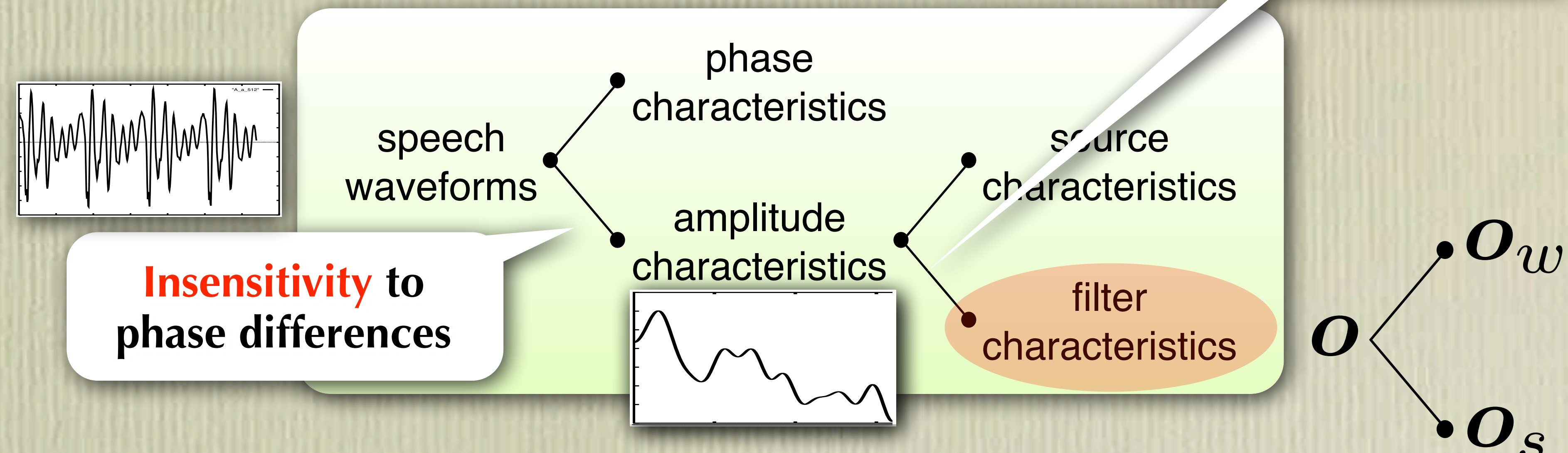
- A major part of the utterances an infant hears are from its parents.
  - The utterances one can hear are extremely speaker-biased.
- Infants don't care about the mismatch in lang. acquisition.
  - Their vocal imitation is not acoustic, it is not impersonation!!



Feature separation to find specific info.

Insensitivity to pitch differences

- **De facto standard acoustic analysis of s**



- **Two acoustic models for speech/speaker recognition**
  - Speaker-independent acoustic model for **w**ord recognition
    - $P(o|w) = \sum_s P(o,s|w) = \sum_s P(o|w,s)P(s|w) \sim \sum_s \underline{P(o|w,s)}P(s)$
  - Text-independent acoustic model for **s**peaker recognition
    - $P(o|s) = \sum_w P(o,w|s) = \sum_w P(o|w,s)P(w|s) \sim \sum_w \underline{P(o|w,s)}P(w)$
  - Require intensive collection
    - $o \rightarrow o_w + o_s$ is possible or not?

Insensitivity in our language learning

Vocal learning (including vocal imitation)

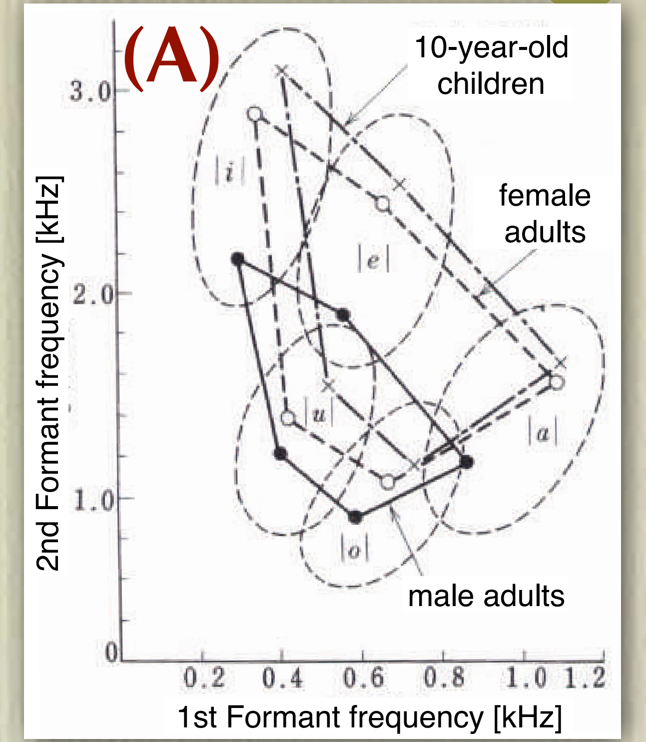
- A imitate(s) B vocally.
  - A: students and B: teachers
  - A: infants and B: parents (caretakers)
  - A: you and B: professional singer (Karaoke)
  - But A do not impersonate B.
    - Acoustically *mis*matched imitation.
- We're very insensitive to speaker identity transmitted via speech.

Acoustically **matched** imitation is often found in

- Autistics (自閉症), who have language disorder [Grandin'96]
- Animals' vocal imitation (birds, dolphins, whales, etc) [Okanoya'08]

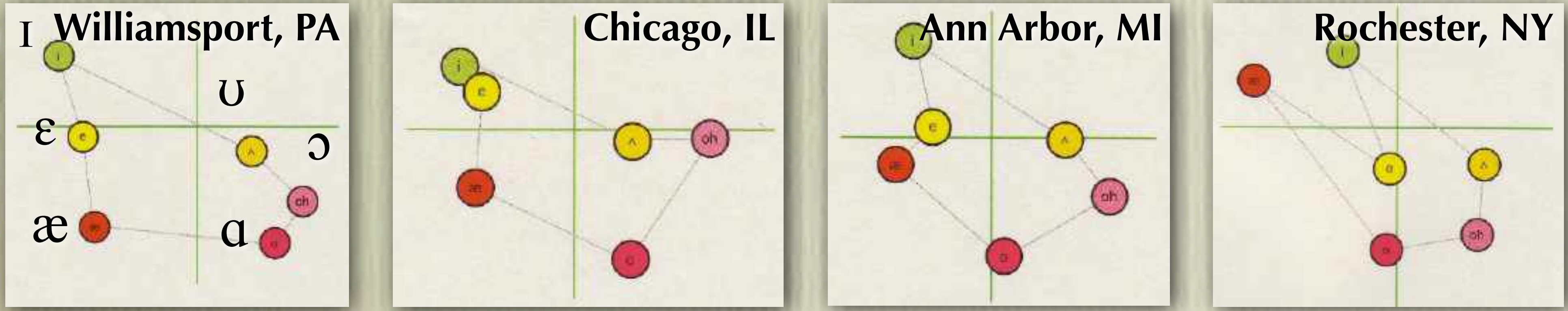
Insensitivity and sensitivity

- **Infants' vocal learning is**
  - insensitive to age and gender differences. **(A)**
  - sensitive to accent differences. **(B)**
- **Infants' vocal learning seems to be**
  - insensitive to feature instances and sensitive to feature relations.
    - **(A)** = instances and **(B)** = relations.
  - Relations, i.e., shape of distribution can be represented geometrically as distance matrix.



formant frequencies of adults and children

(B)



Distribution of normalized formants among AE dialects [Labov et al.'05]

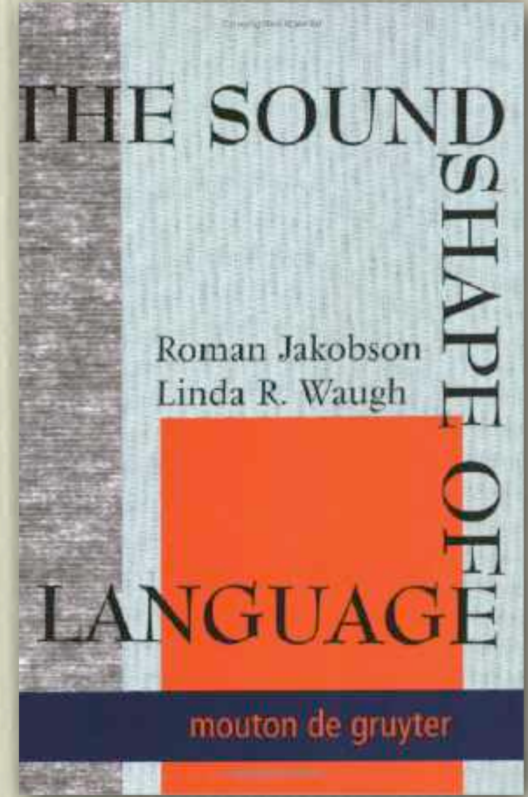
A claim found in classical linguistics

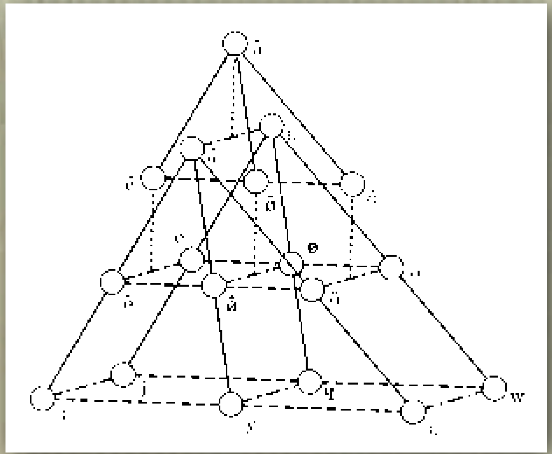
Theory of relational invariance [Jakobson+'79]

- Also known as theory of distinctive features
- Proposed by R. Jakobson

We have to put aside the accidental properties of individual sounds and substitute a general expression that is the common denominator of these variables.

Physiologically identical sounds may possess different values in conformity with the whole sound system, i.e. in their relations to the other sounds.





Invariant pitch perception against its bias

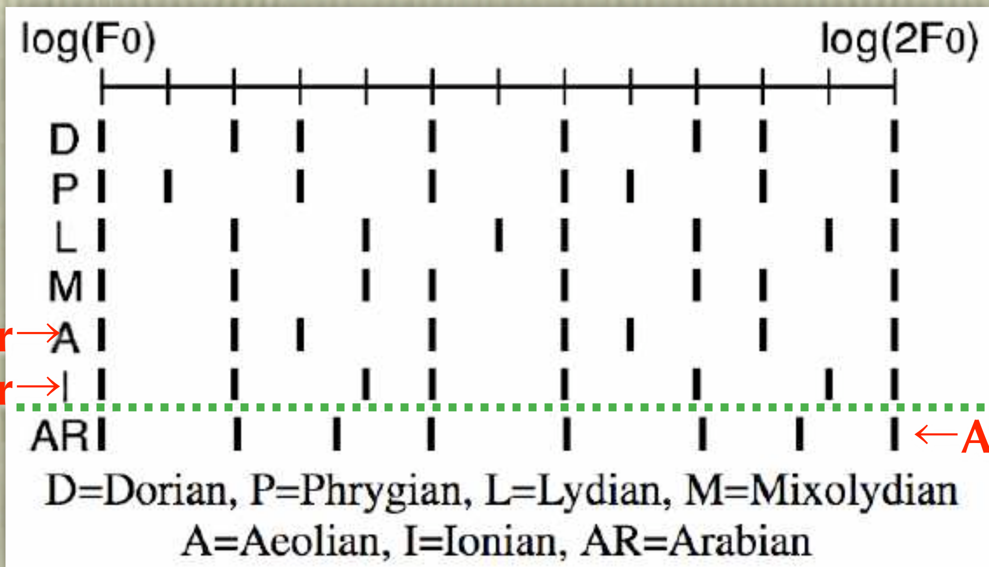
Key change (transposition) of a melody [Higashikawa'05]

1
2


- Absolute (perfect) pitch (Do, Re, Mi... = pitch names) **(音名)**
  - 1 = So, Mi, So, Do, La, Do, Do, So.   2 = Re, Ti, Re, So, Mi, So, So, Re.
- Relative pitch with transcription ability (Do, Re... = syllable names)
  - 1 = So, Mi, So, Do, La, Do, Do, So.   2 = So, Mi, So, Do, La, Do, Do, So.
    (階名)
- Relative pitch without transcription ability
  - 1 = La, La, La, La, La, La, La, La.   2 = La, La, La, La, La, La, La, La
- Different / identical tones are claimed to be identical / different.
- Not fundamental frequency (absolute property) of each tone, but it only matters **what contrast each tone has to its surrounding tones.**

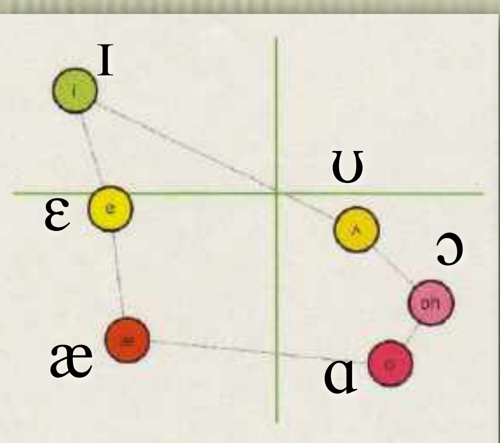
Relative pitch vs. relative timbre

Key-invariant arrangement of tones and its variants

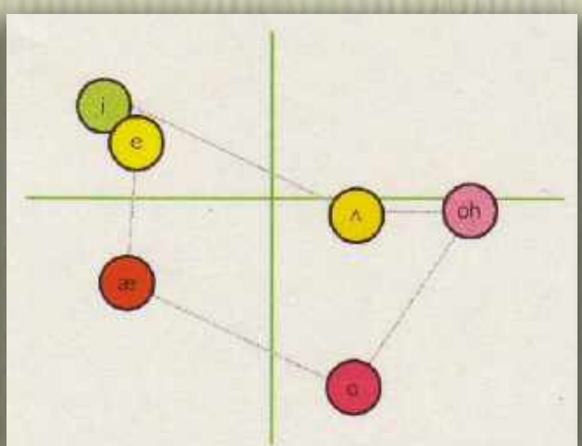


- Western = 5 whole + 2 semi
- D to I = classical church music
- Arabic = with non-semi intervals
  - Western music in Arabic scale

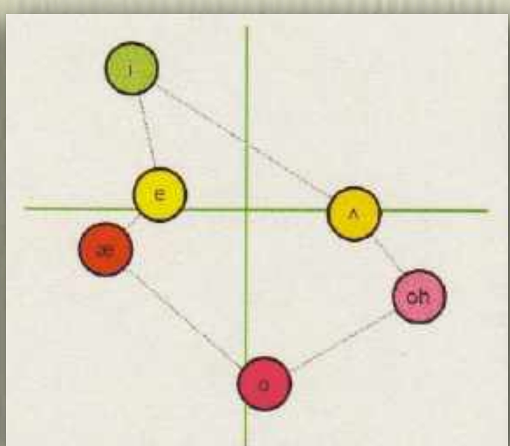
Spk-invariant arrangement of vowels and its variants



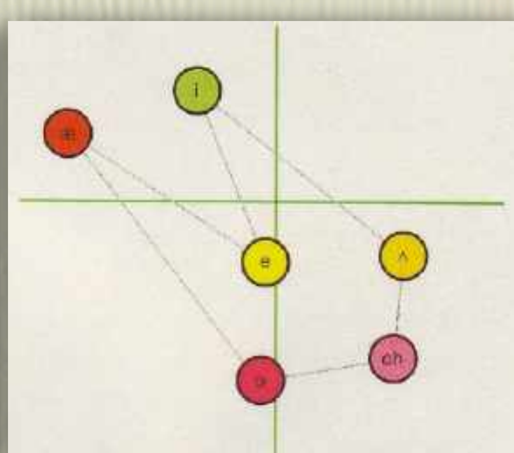
Williamsport, PA



Chicago, IL



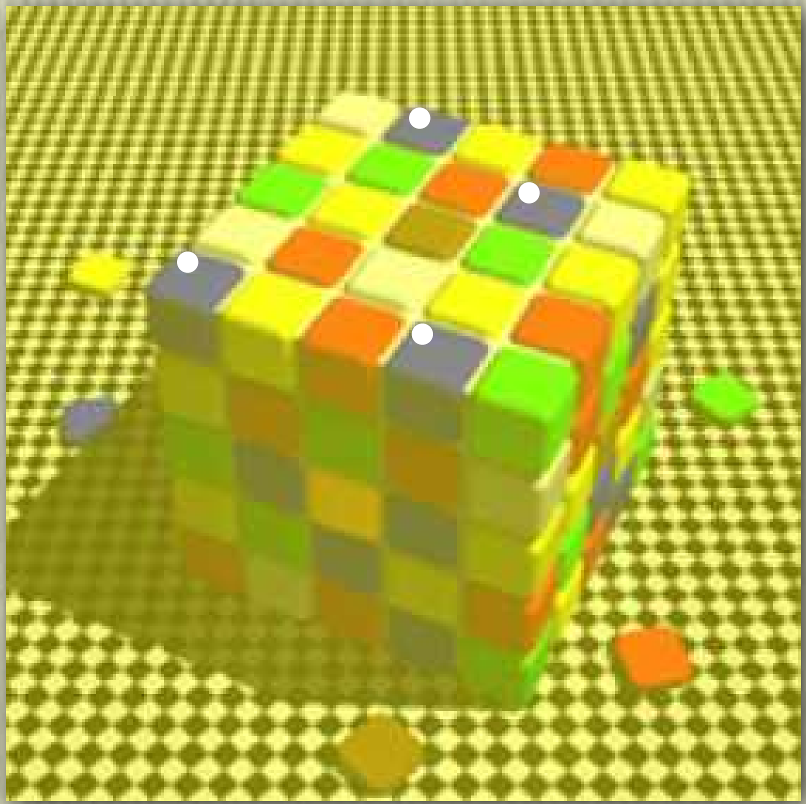
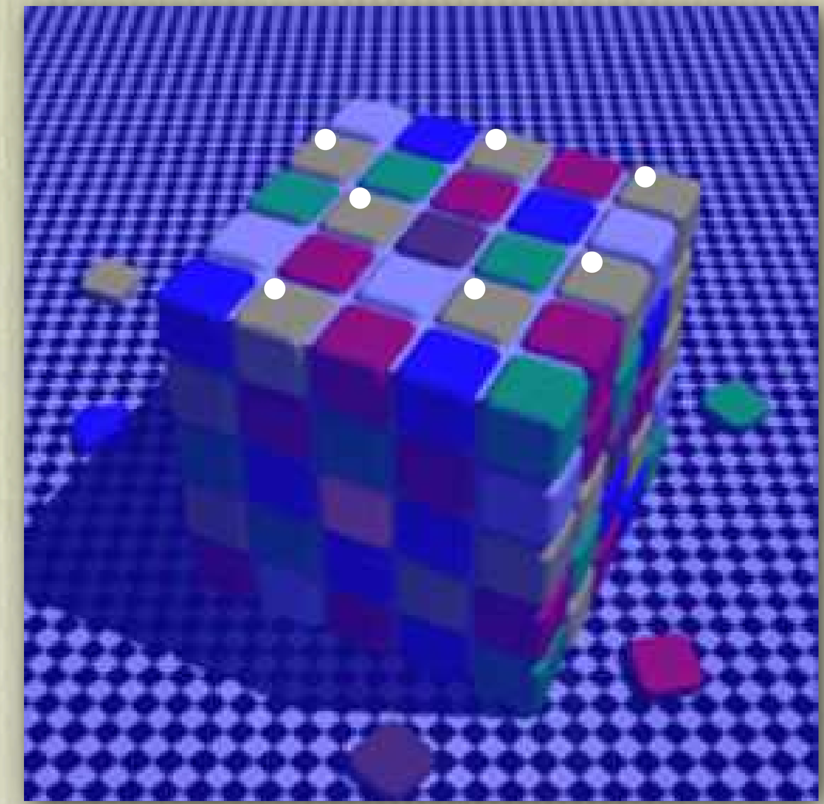
Ann Arbor, MI



Rochester, NY

Invariant color perception against its bias

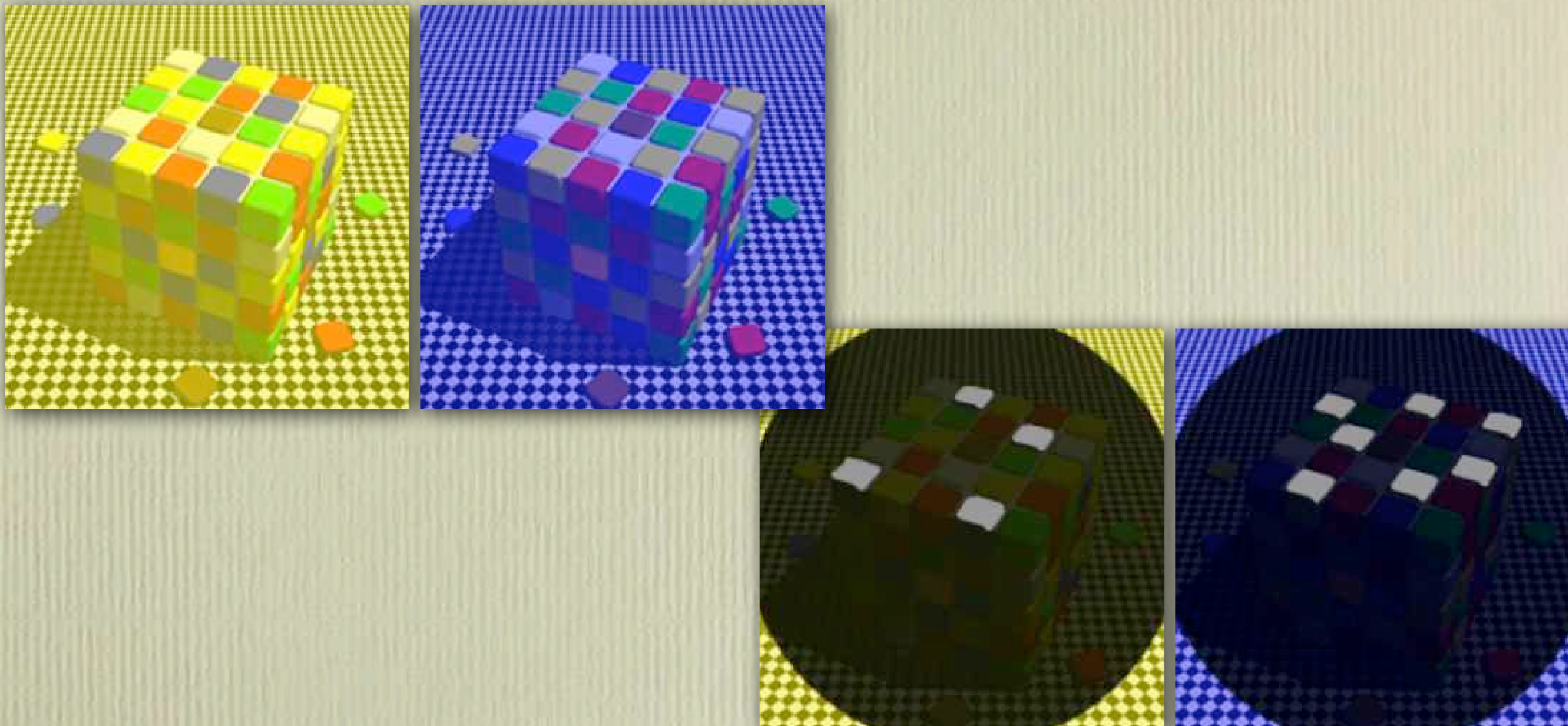
The Rubik's cube seen through colored glasses [Lotto'99]

- We perceive that the two cubes are identical.
- Different / identical colors are claimed to be identical / different.
- Not only wavelength (absolute property) of each patch, but also it matters **what contrast each patch has to its surrounding patches.**

An evolutional point of view

How old is the relative perception in evolution? [Briscoe'01]



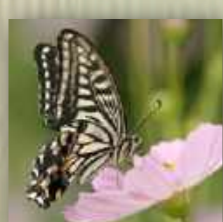
An evolutional point of view

How old is the relative perception in evolution? [Hauser'03]

1

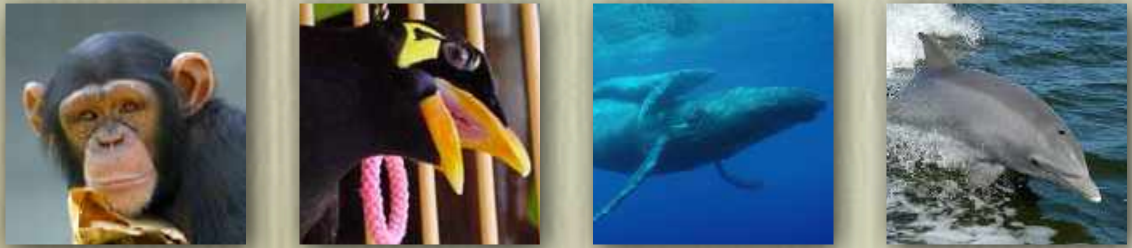
2

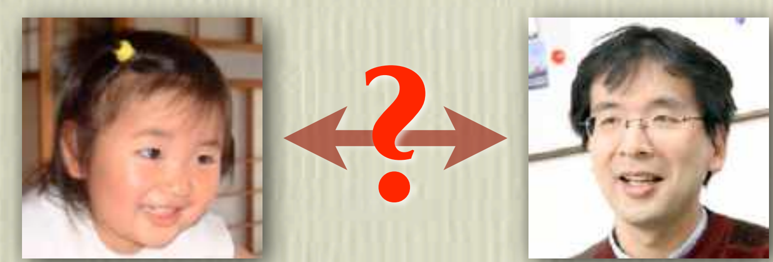
1 = 2

Language acquisition through vocal imitation

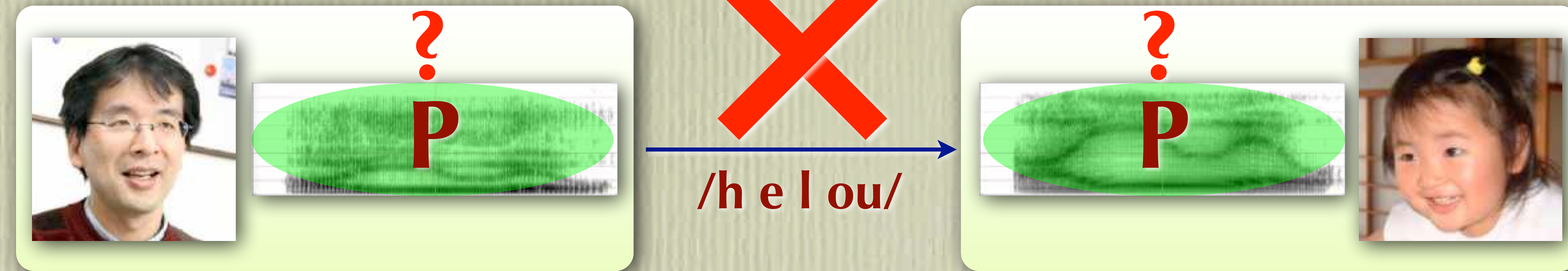
- **VI = children's active imitation of parents' utterances**
  - Language acquisition is based on vocal imitation [Jusczyk'00].
  - VI is very rare in animals. No other primate does VI [Gruhn'06].
  - Only small birds, whales, and dolphins do VI [Okanoya'08].
- **A's VI = acoustic imitation but H's VI ≠ acoustic = ??**
  - Acoustic imitation performed by myna birds [Miyamoto'95]
    - They imitate the sounds of cars, doors, dogs, cats as well as human voices.
    - Hearing a very good myna bird say something, one can guess its owner.
  - Beyond-scale imitation of utterances performed by children
    - No one can guess a parent by hearing the voices of his/her child.
    - Very weird imitation from a viewpoint of animal science [Okanoya'08].





Language acquisition through vocal imitation

- **Utterance → symbol sequence → production of each sym.**



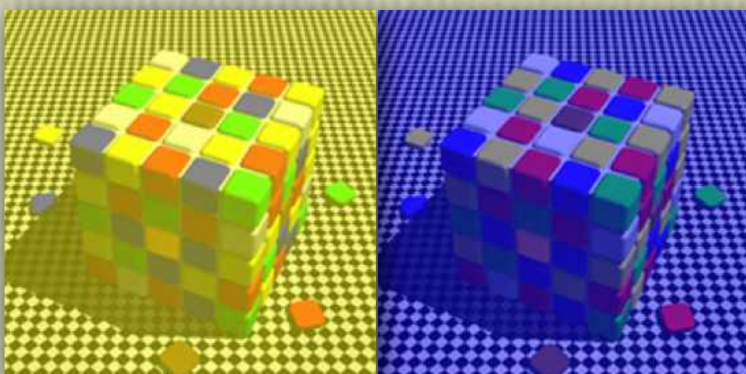
  - Phonemic awareness is too poor to decompose an utterance.

- **Several answers from developmental psychology**
  - Holistic/related sound patterns embedded in utterances
    - Holistic wordform [Kato'03]
    - Word Gestalt [Hayakawa'06]
    - Related spectrum pattern [Lieberman'80]
  - The patterns have to include no speaker information in themselves.
    - If they do it, children have to try to impersonate their fathers.
    - What is the speaker-invariant and holistic pattern in an utterance?

Invariant timbre perception against its bias

Invariant and constant perception wrt. color and pitch

- Contrast-based information processing is important.
- Holistic & relational processing enables element identification.



Invariant and constant perception wrt. timbre

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A new framework for “human-like” speech machines #2

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Menu of the last four lectures

- **Robust processing of easily changeable stimuli**
  - Robust processing of general sensory stimuli
  - Any difference in the processing between humans and animals?
- **Human development of spoken language**
  - Infants' vocal imitation of their parents' utterances
  - What acoustic aspect of the parents' voices do they imitate?
- **Speaker-invariant holistic pattern in an utterance**
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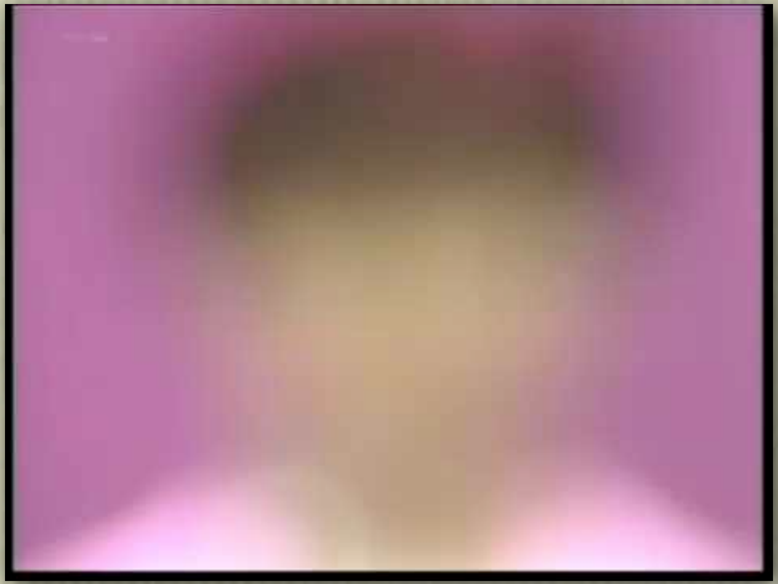
  - Implementation of word Gestalt as relative timbre perception
  - Application of speech structure to robust speech processing
- **Radical but interesting discussion**
  - An interesting link to some behaviors found in language disorder
  - An interesting thought experiment

Impersonation vs. non-impersonation

- A very talented impersonator of Seiko Matsuda



Seiko's impersonator

Seiko's daughter

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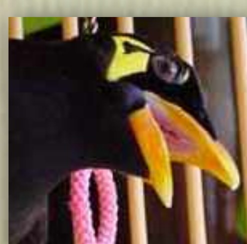
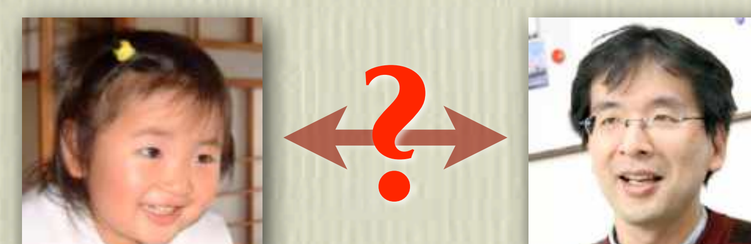


"I impersonate a language teacher."

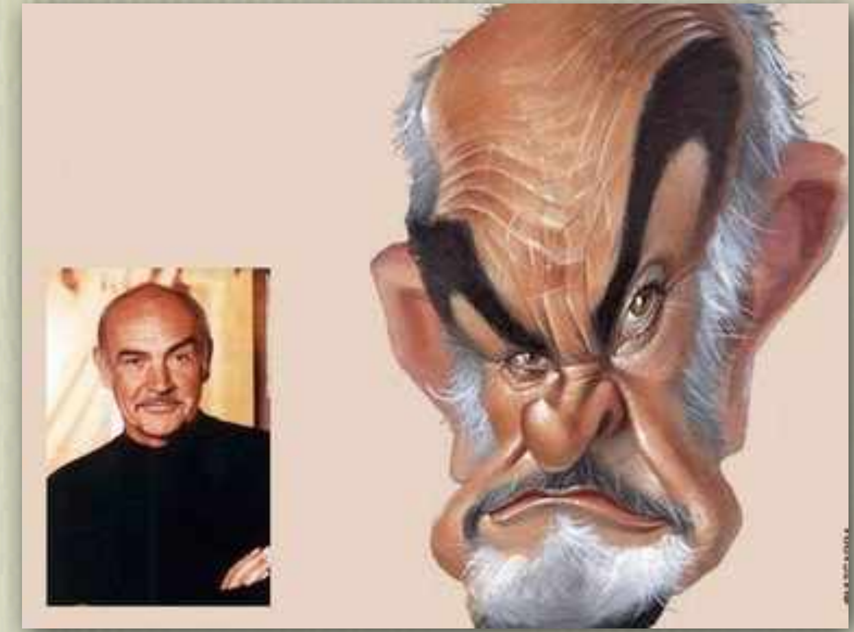
Some comments from an autistic women

- Q: "How do you do vocal imitation in a Karaoke box or in a class of foreign languages?"
- A: "I impersonate a professional singer or a teacher."
  - B: "Acoustic imitation seems to be her default strategy of vocal imitation."
- A: "Spoken language is difficult to use."
  - A: "Written language and sign language are much easier."

TV program with talented impersonators

- **Can you enjoy such a TV program?**
  - I cannot understand what is amusing.
- **Can you perceive any similarity between these pictures?**
  - No. I believe that this is much similar to this picture.
- **Robust perception of equivalence against deformation**
  - Our perception is very robust with a certain kind of deformation.





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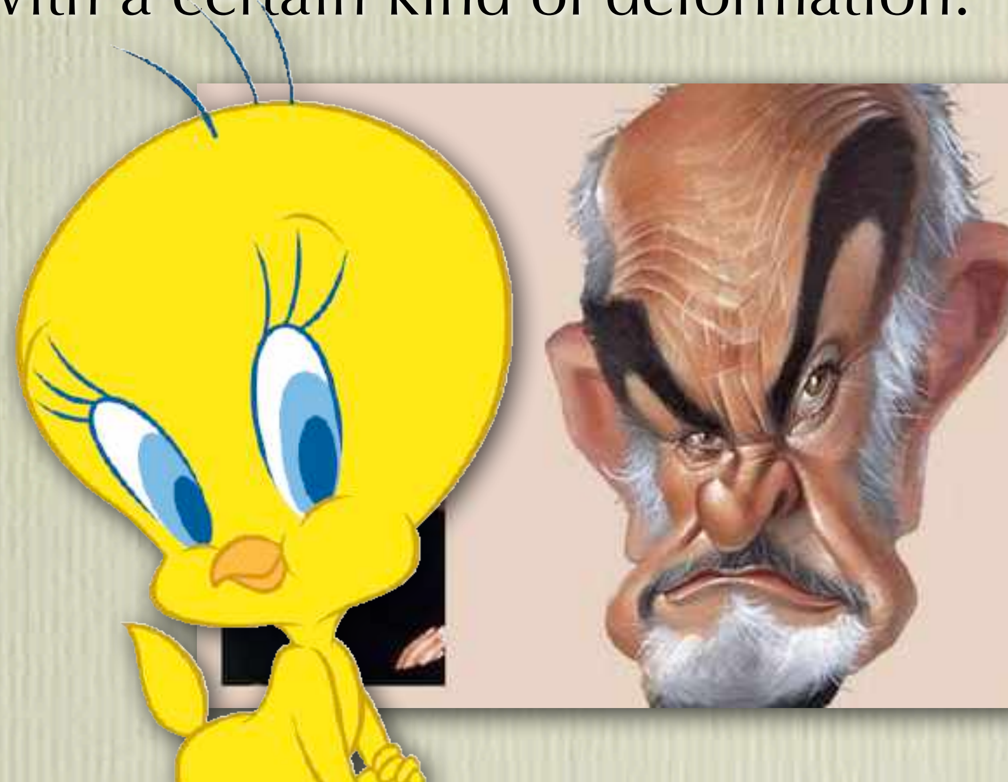
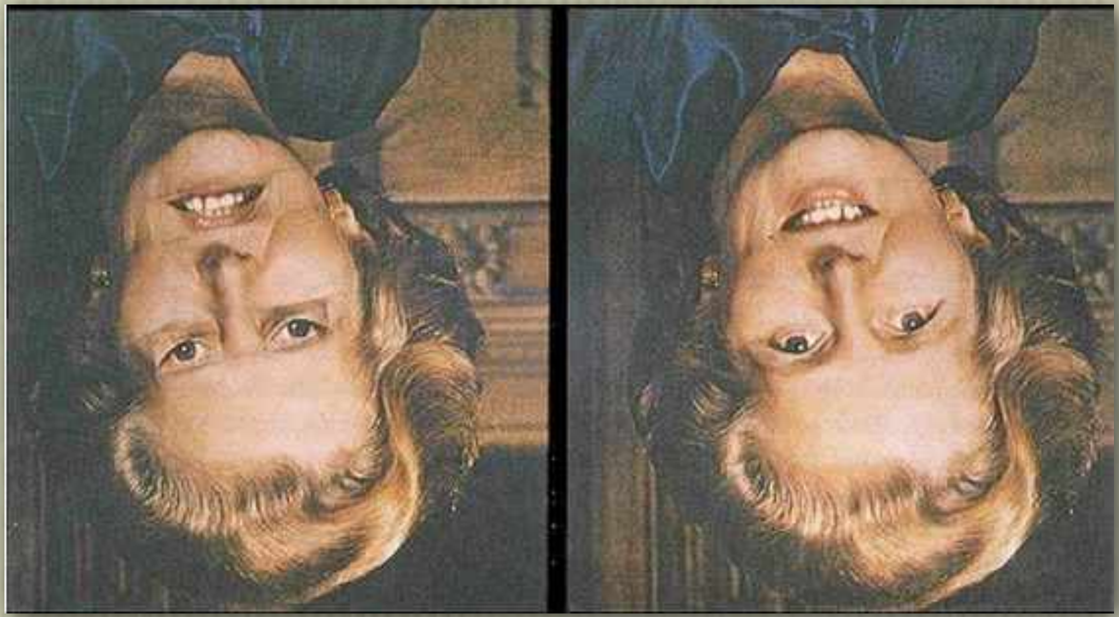


Non-robustness with other deformation

- Thatcher illusion



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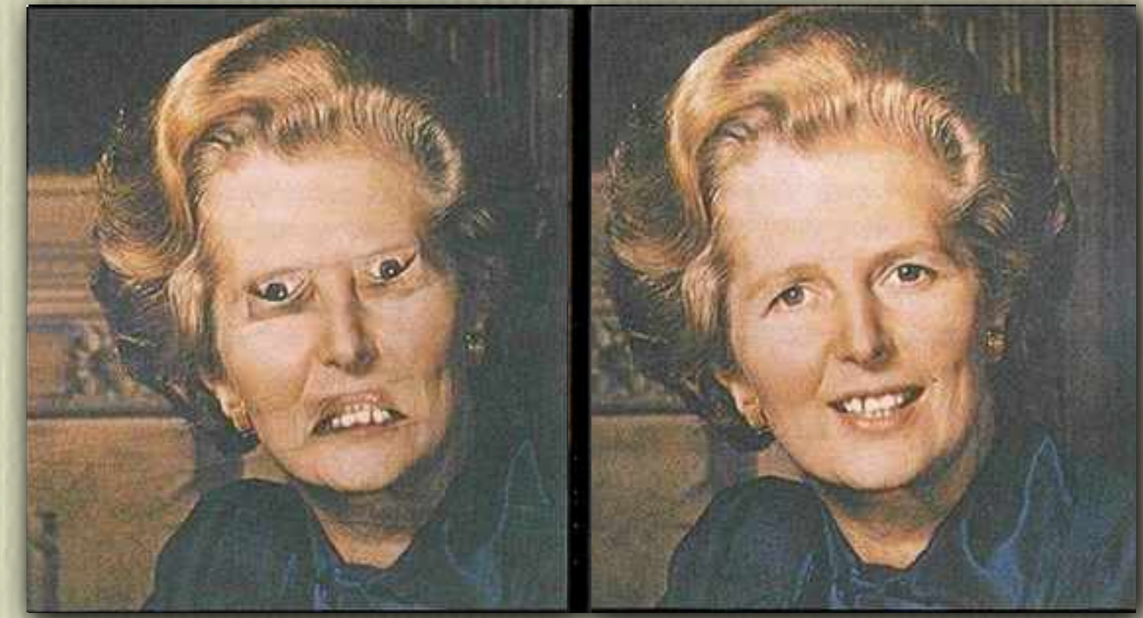

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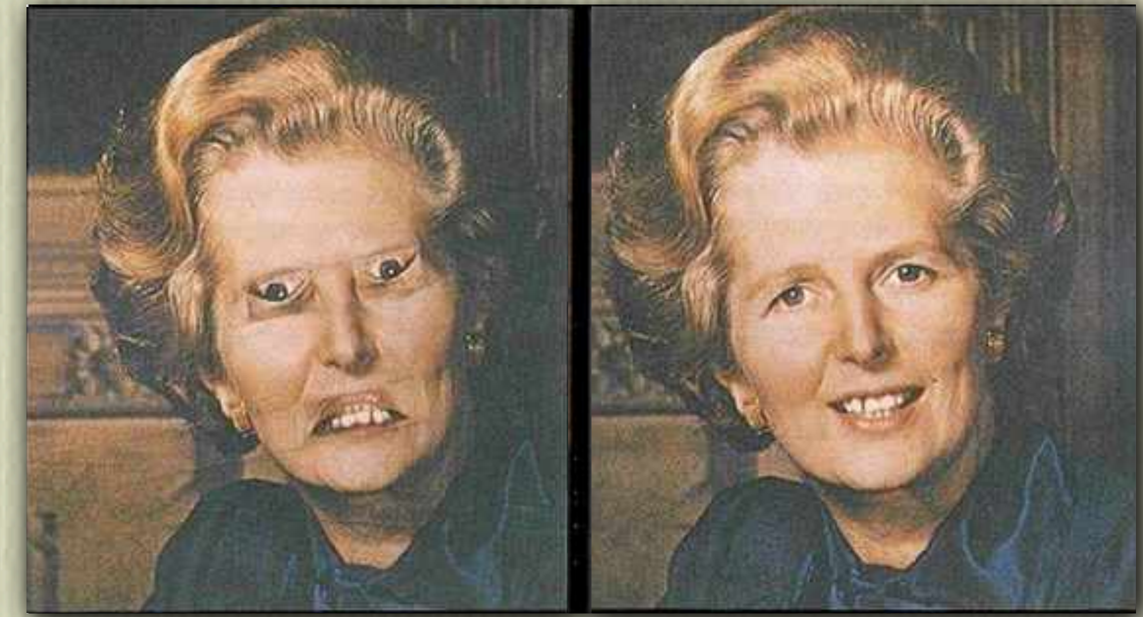
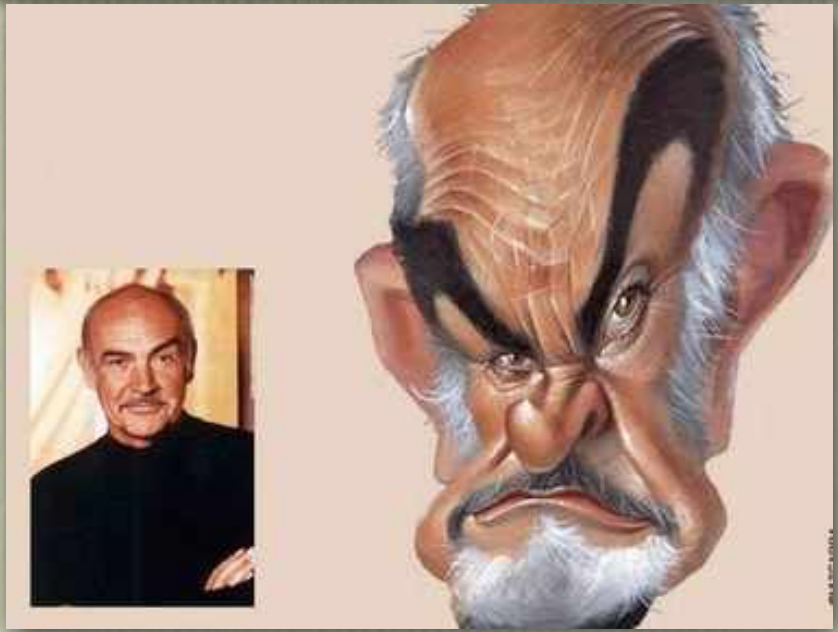




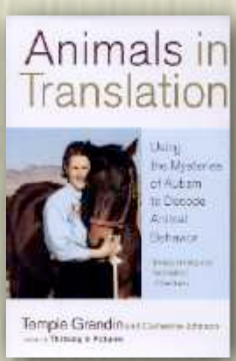
Claims from a professor of animal sciences

Dr. Temple Grandin @ Colorado State University

- She is herself autistic (Asperger syndrome).
- Autistics often imitate the utterances of TV/radio commercials.
  - TV/radio often gives “acoustically” identical utterances.
  - The utterances from family members change “acoustically” time to time.
- They often imitate the sounds of objects such as cars, doors, etc.
  - These sounds, including human voices, are just acoustic sounds.

Interesting claims from her

- Similarity of information processing between animals and autistics
- Storing the detailed aspects of input stimuli as they are in the brain
  - Animal : local / detail / absolute
  - Human : holistic / abstract / relative
    - Good ability to generalize



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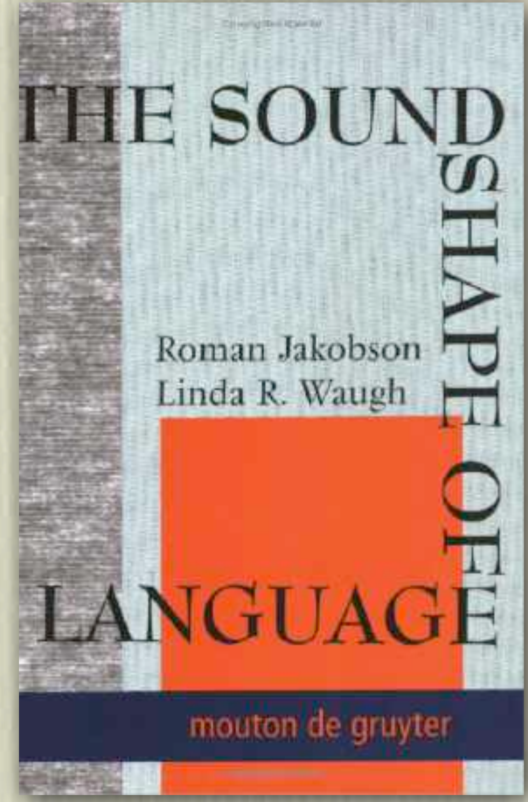
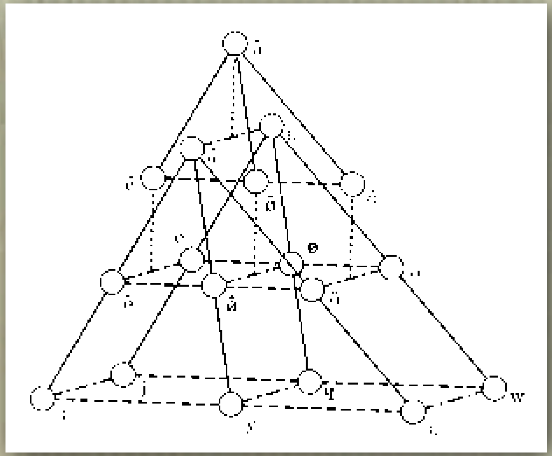
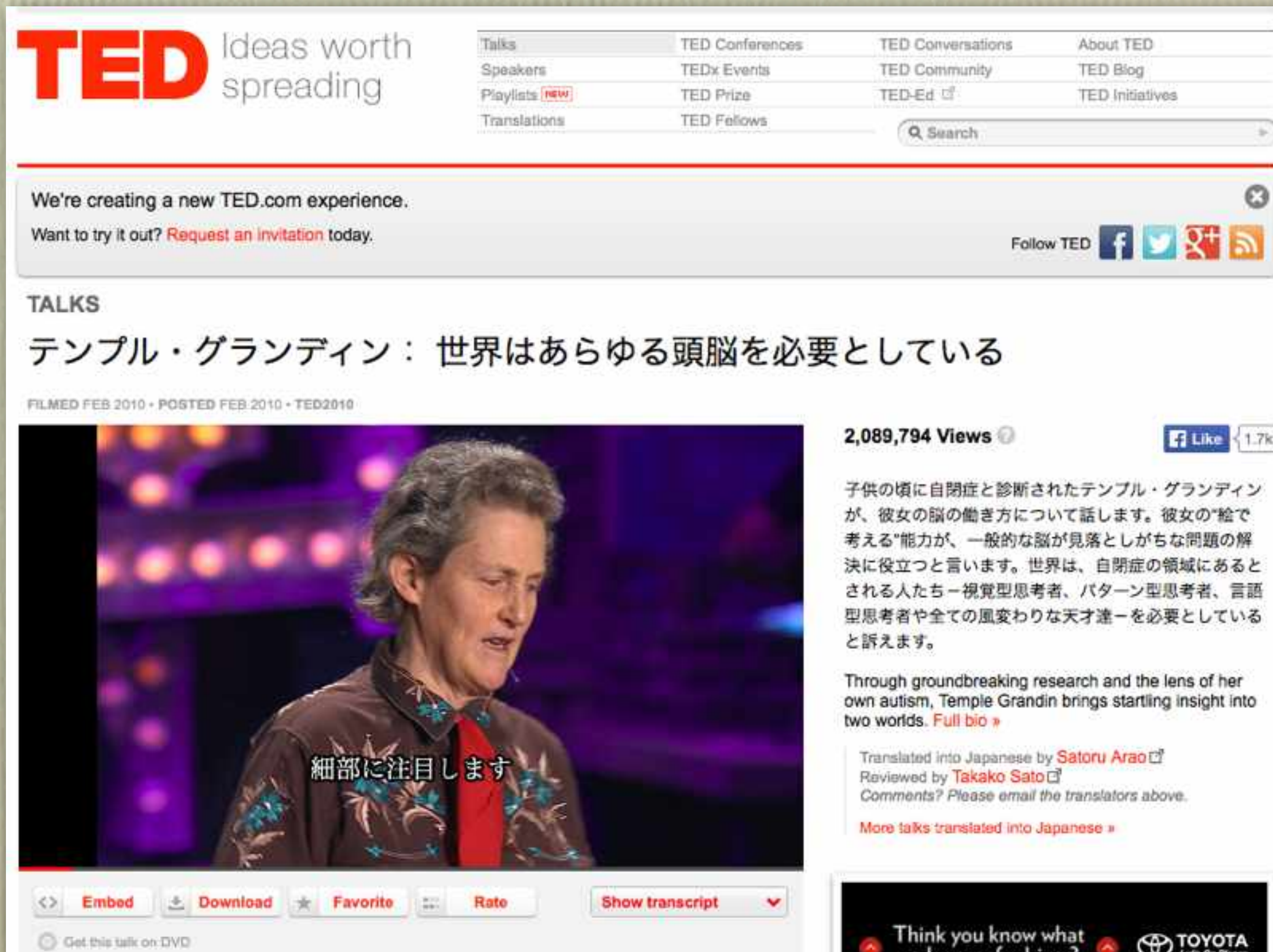




Temple Grandin's TED talk

- You can hear her talk at TED.



A book written by an autistic boy

"I can understand my mother's utterances only".

どこにいてもどんなときでも、僕がわかる言葉は、お母さんだけです。

僕は、どうして今まで言葉が理解できないのか、わかりませんでした。他のみんなが指示されたことにすぐに反応できて、その通りに動けることが不思議でした。

僕には聞こえないのです。

音は聞こえているけれど、意味になって頭の中に入ってこないのです。話しているのが本人だとわかれば、慣れれば言っていることはわかります。でも、同じ人でも場所や状況が違うと、その人だということがわからないのです。

僕はお母さんの言うことならすべてわかります。それは、第1に安心感、第2に言葉のリズムや高低が良くわかっていること、第3に話の予測がつきやすいためでしょう。

http://www.nhk.or.jp/school-blog/300/195393.html

Insensitivity and sensitivity

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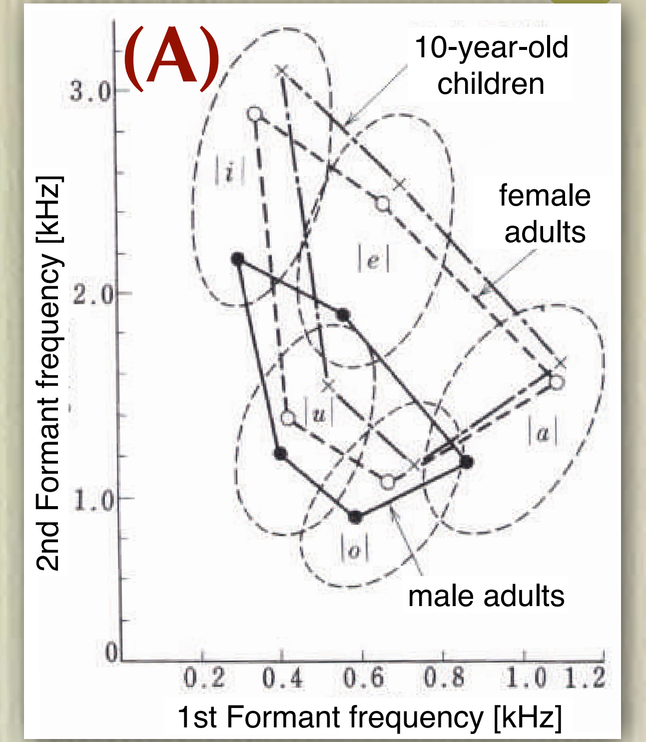
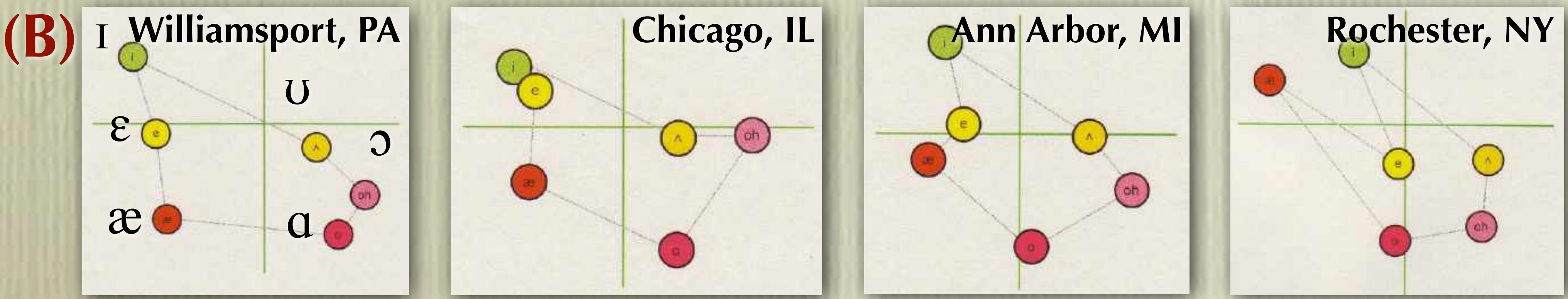


formant frequencies of adults and children



Distribution of normalized formants among AE dialects [Labov et al.'05]

An interesting book

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  - Robust processing of general sensory stimuli
  - Any difference in the processing between humans and animals?
- **Human development of spoken language**
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  - An interesting link to some behaviors found in language disorder
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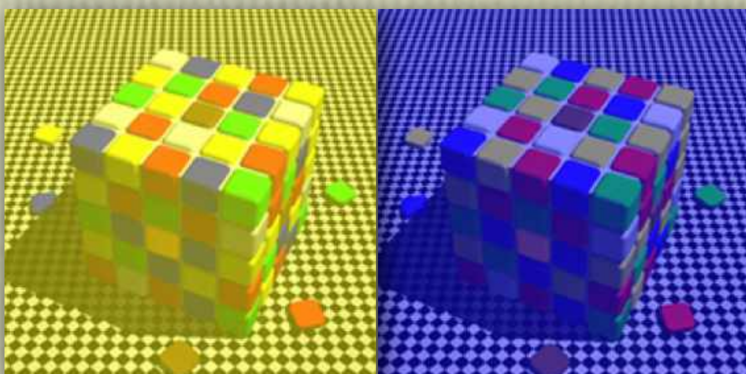
Invariant timbre perception against its bias

Invariant and constant perception wrt. color and pitch

- Contrast-based information processing is important.
- Holistic & relational processing enables element identification.



Invariant and constant perception wrt. timbre

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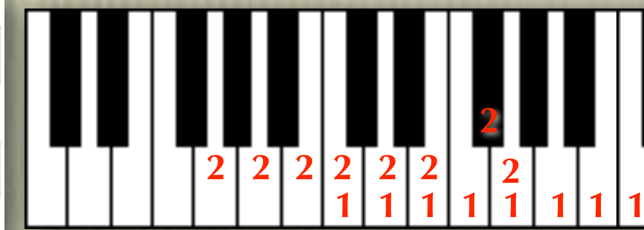
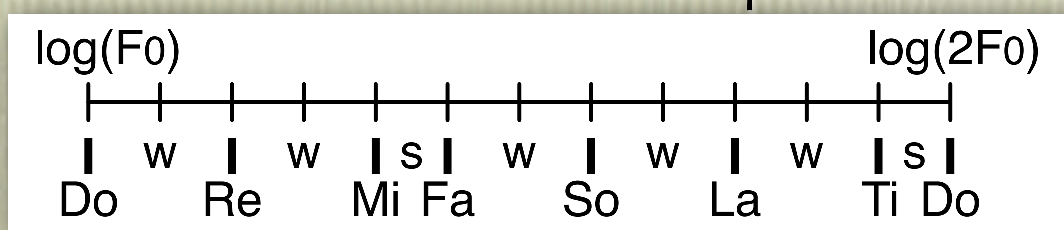
Invariant pitch perception against its bias

A melody and its transposed version [Higashikawa'05]

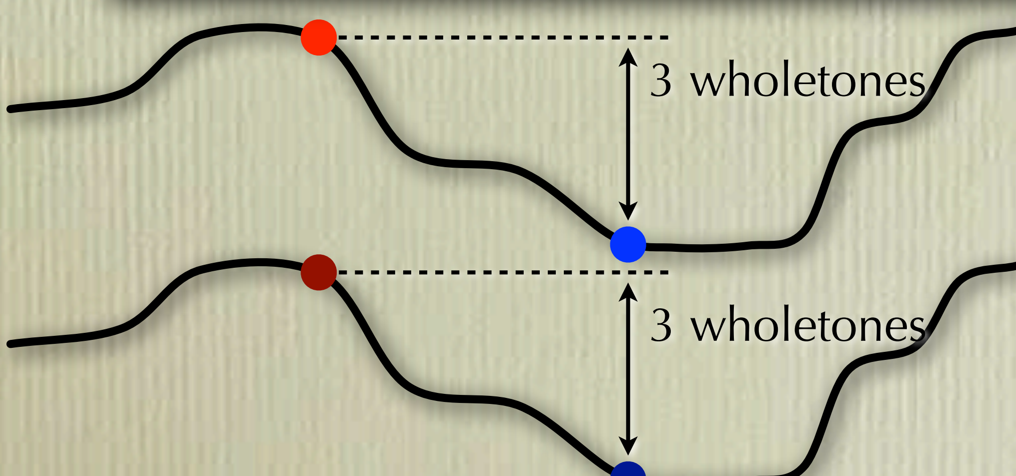
1)
2)



- Listeners with RP can perceive the same sound name sequence.
  - So Mi So Do / Ra Do Do So / So Do Re Mi Re Do / Re
  - The same sound distribution pattern is found in 1) and 2).

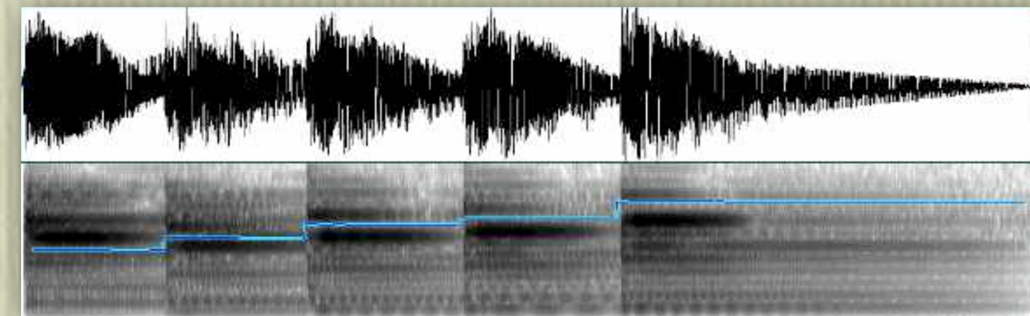


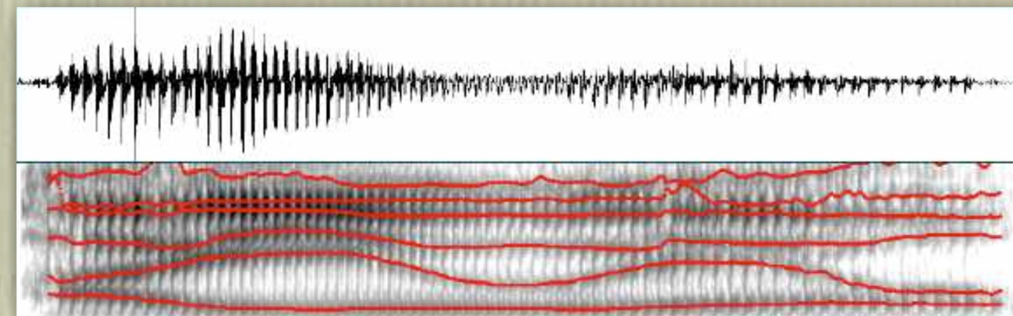
Whole = 2 Semi

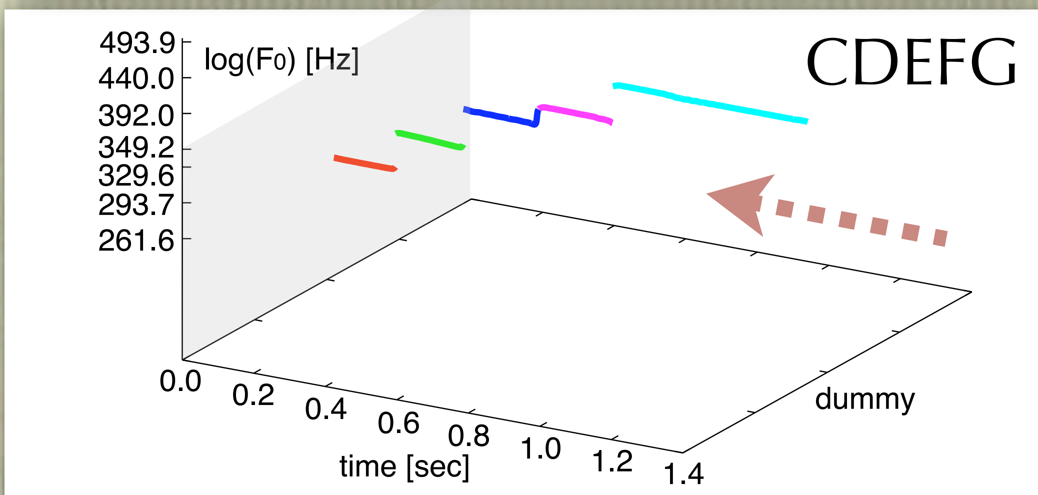


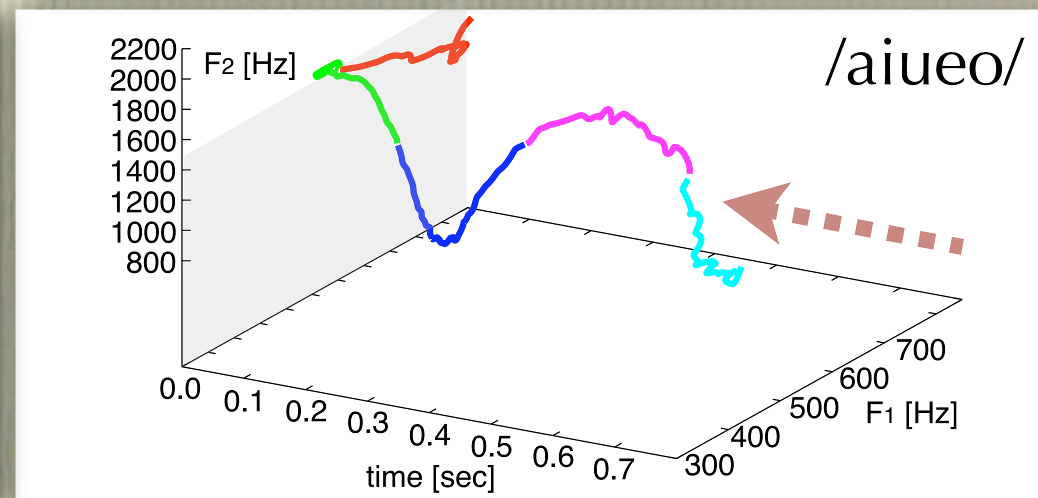
●● and ●● have to be fa & ti or ti & fa due to contrastive constraints.

Relative pitch vs. relative timbre



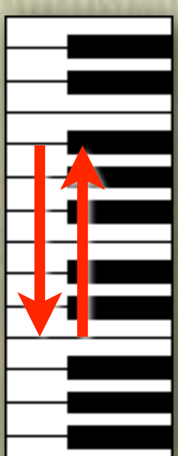




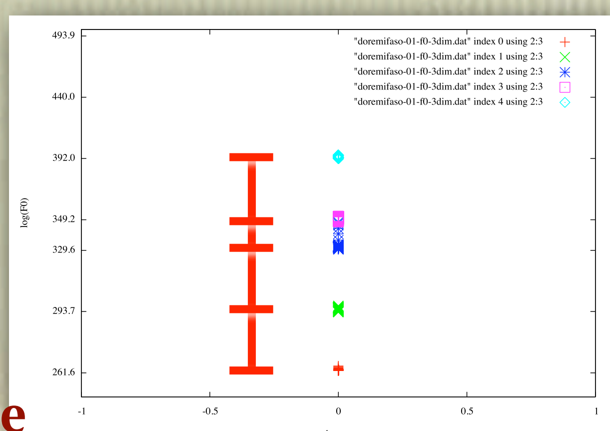


pitch modulation

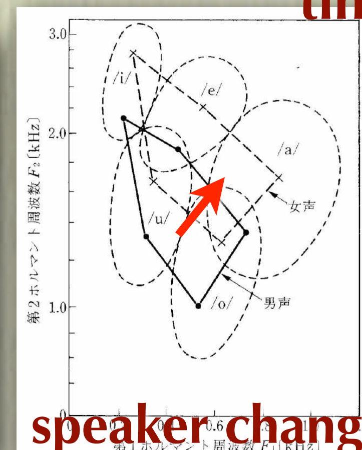
timbre modulation



log(F0)

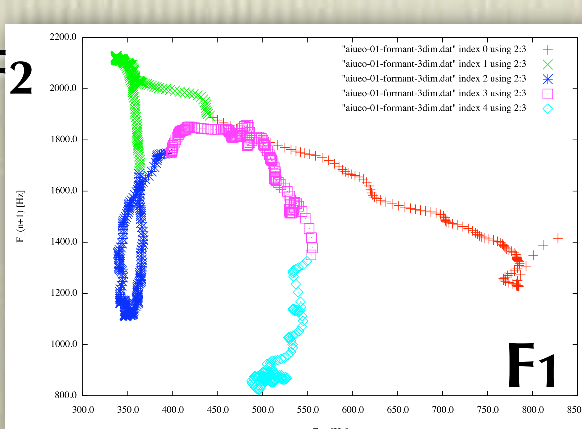


key change

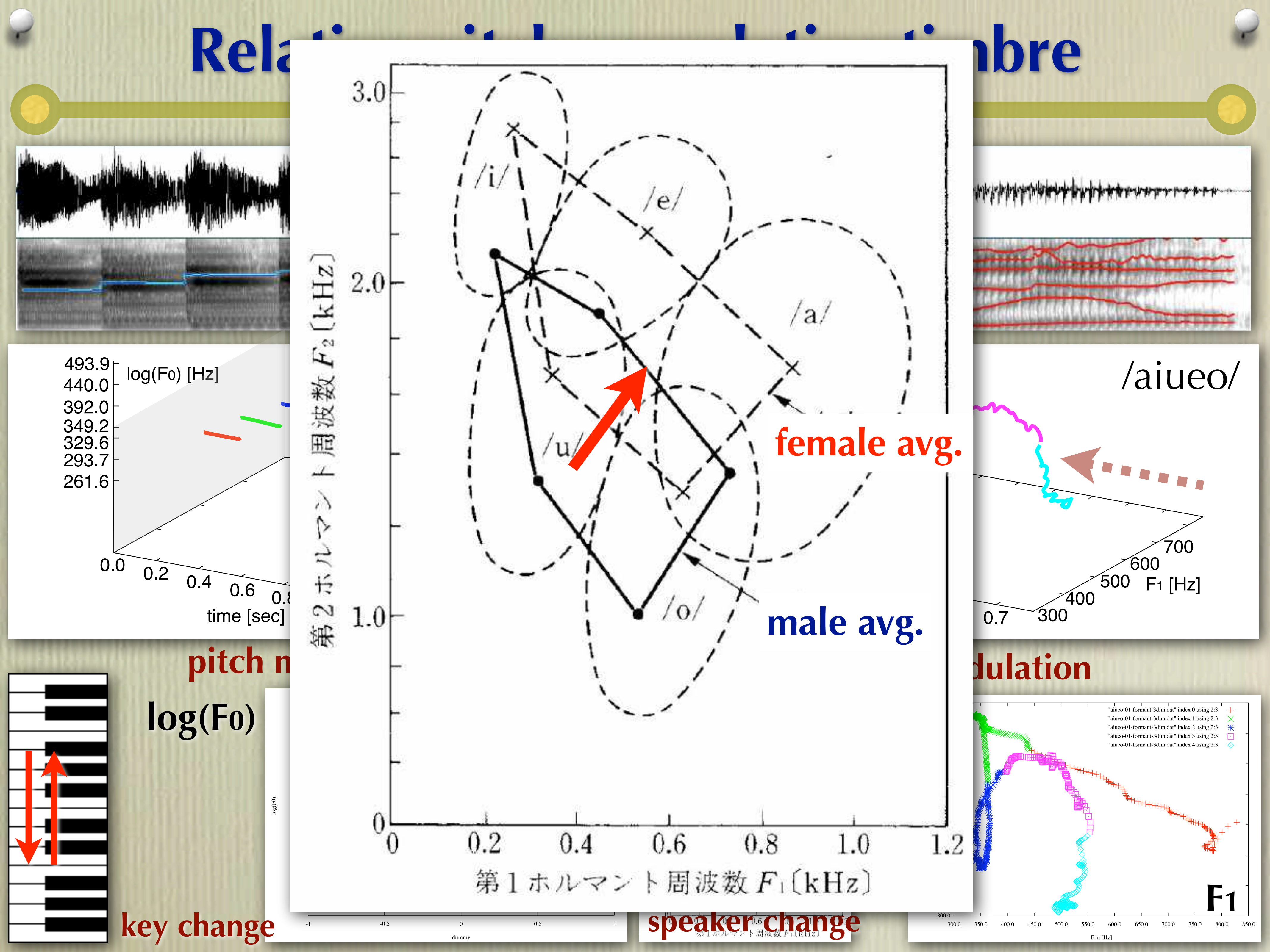


speaker change

F2



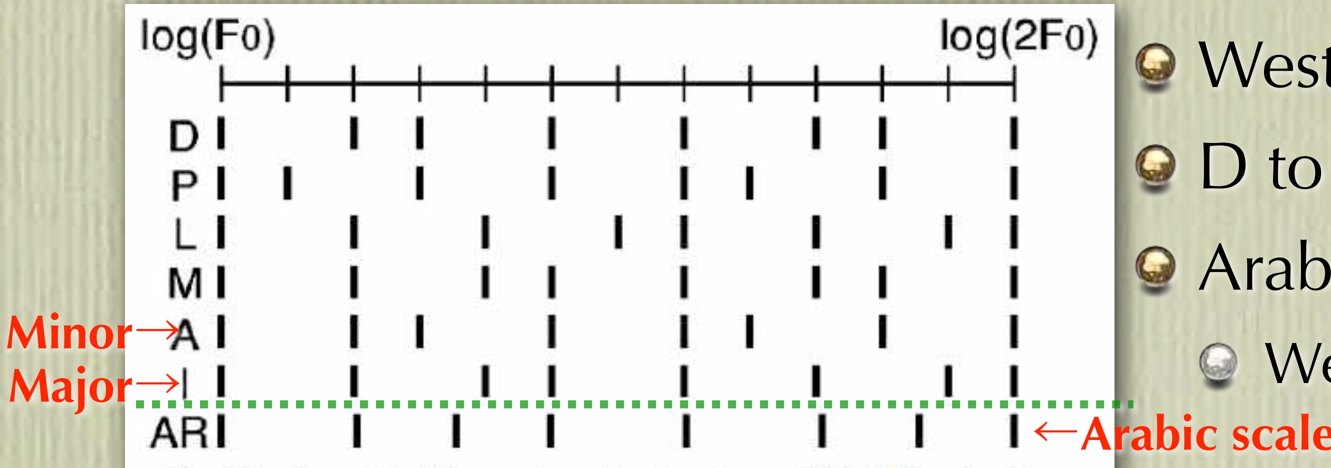
F1



Rela
bre
493.9
440.0
392.0
349.2
329.6
293.7
261.6
log(F0) [Hz]
0.0
0.2
0.4
0.6
time [sec]
pitch m
log(F0)
key change
3.0
2.0
1.0
0
0.2
0.4
0.6
0.8
1.0
1.2
第2ホルマント周波数 F2〔kHz〕
第1ホルマント周波数 F1〔kHz〕
/i/
/e/
/a/
/u/
/o/
female avg.
male avg.
speaker change
/aiueo/
700
600
500
400
300
F1 [Hz]
0.7
dulation
F1

Relative pitch vs. relative timbre

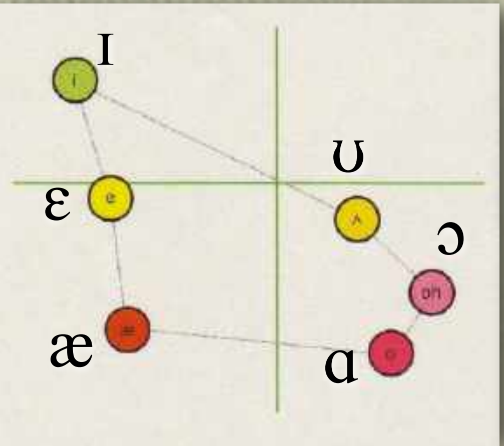
Key-invariant arrangement of tones and its variants



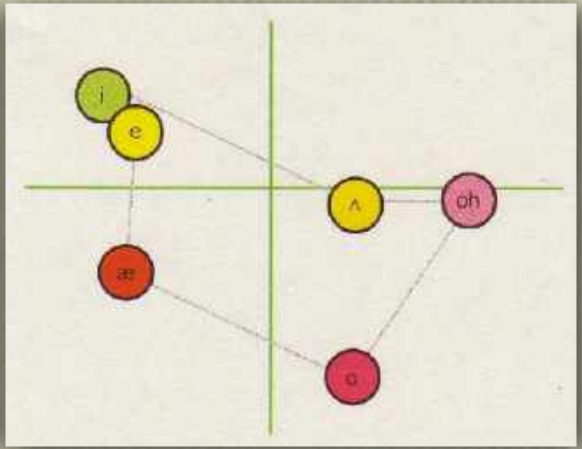
D=Dorian, P=Phrygian, L=Lydian, M=Mixolydian
A=Aeolian, I=Ionian, AR=Arabian

- Western = 5 whole + 2 semi
- D to I = classical church music
- Arabic = with non-semi intervals
  - Western music in Arabic scale

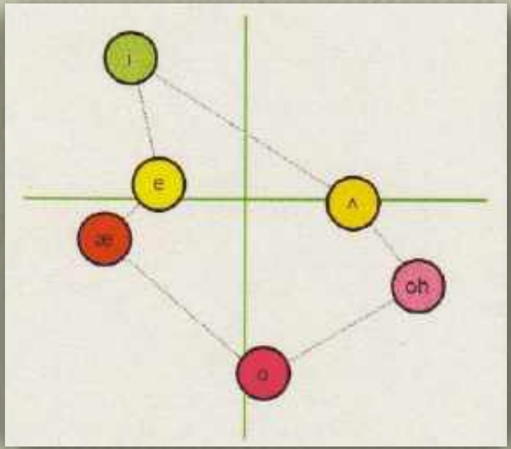
Spk-invariant arrangement of vowels and its variants



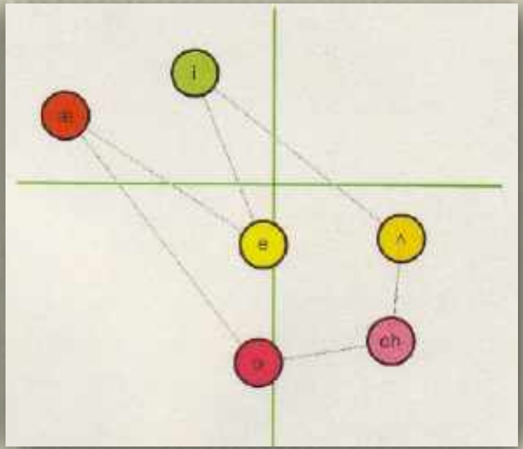
Williamsport, PA



Chicago, IL

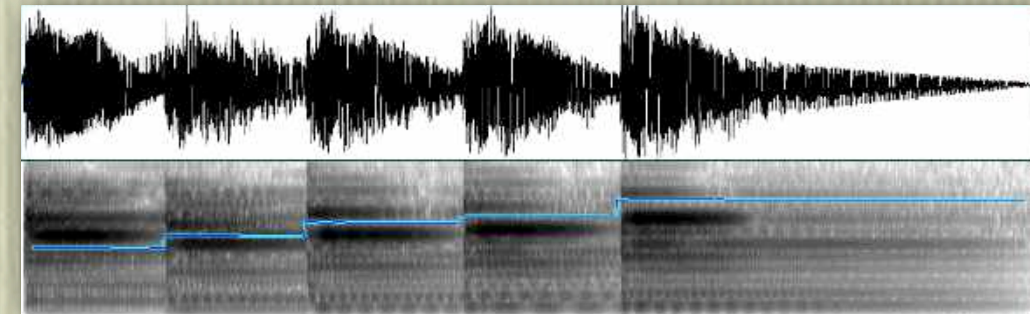


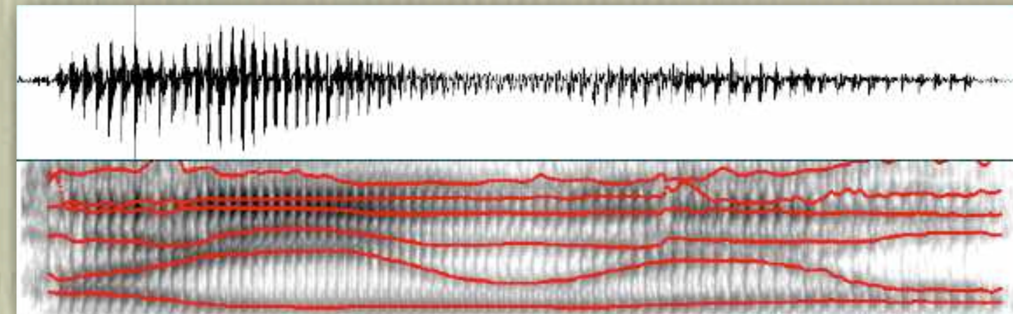
Ann Arbor, MI

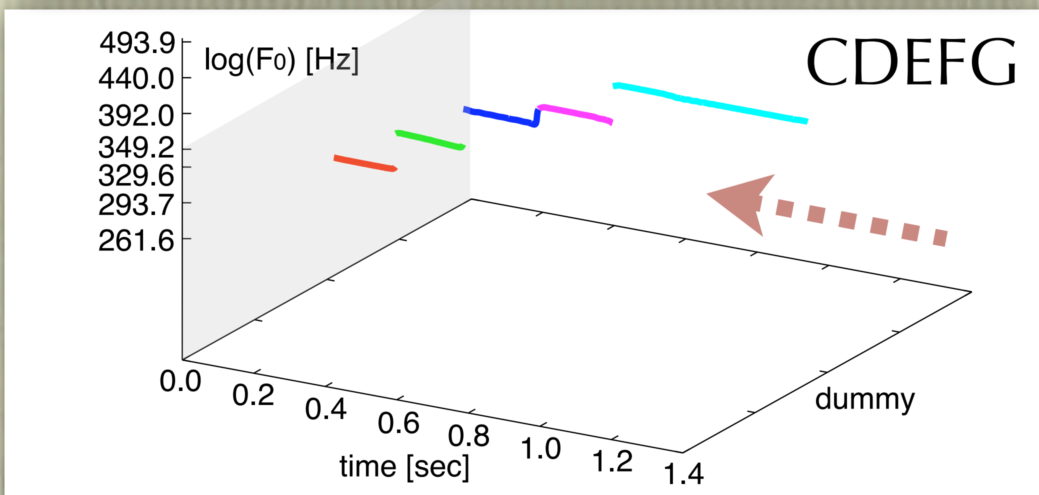


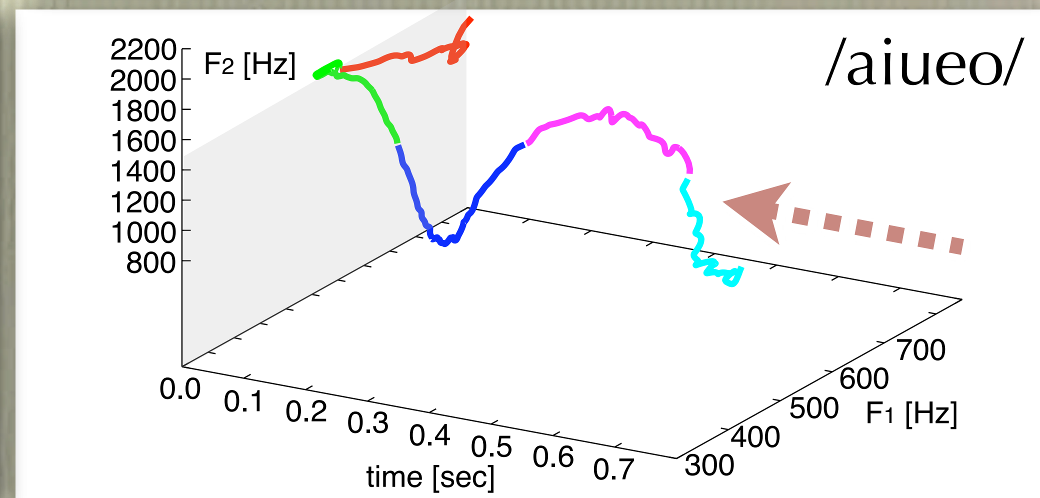
Rochester, NY

Relative pitch vs. relative timbre



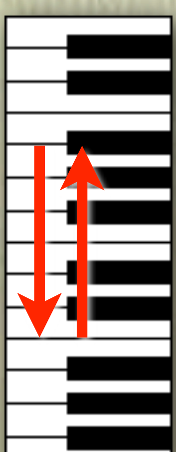




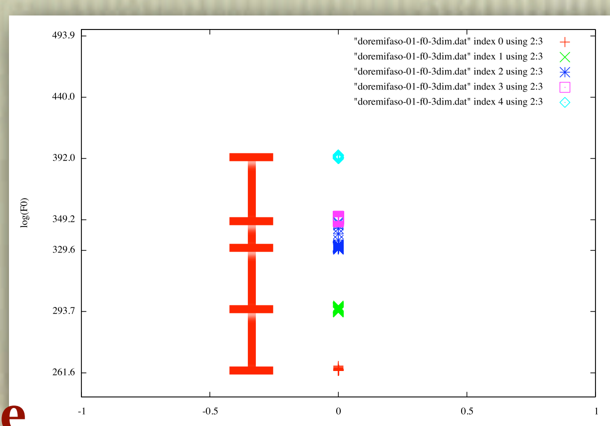


pitch modulation

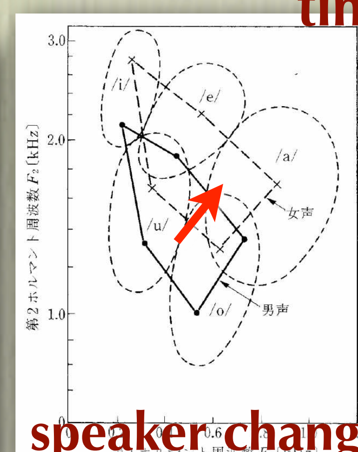
timbre modulation



log(F0)

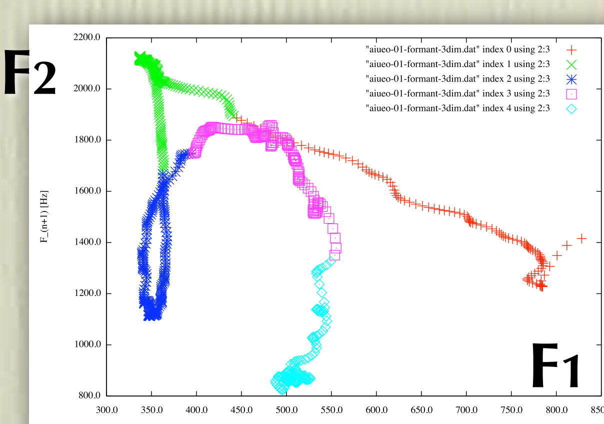


key change



speaker change

F2



F1

Invariant pitch perception against its bias

Key change (transposition) of a melody [Higashikawa'05]

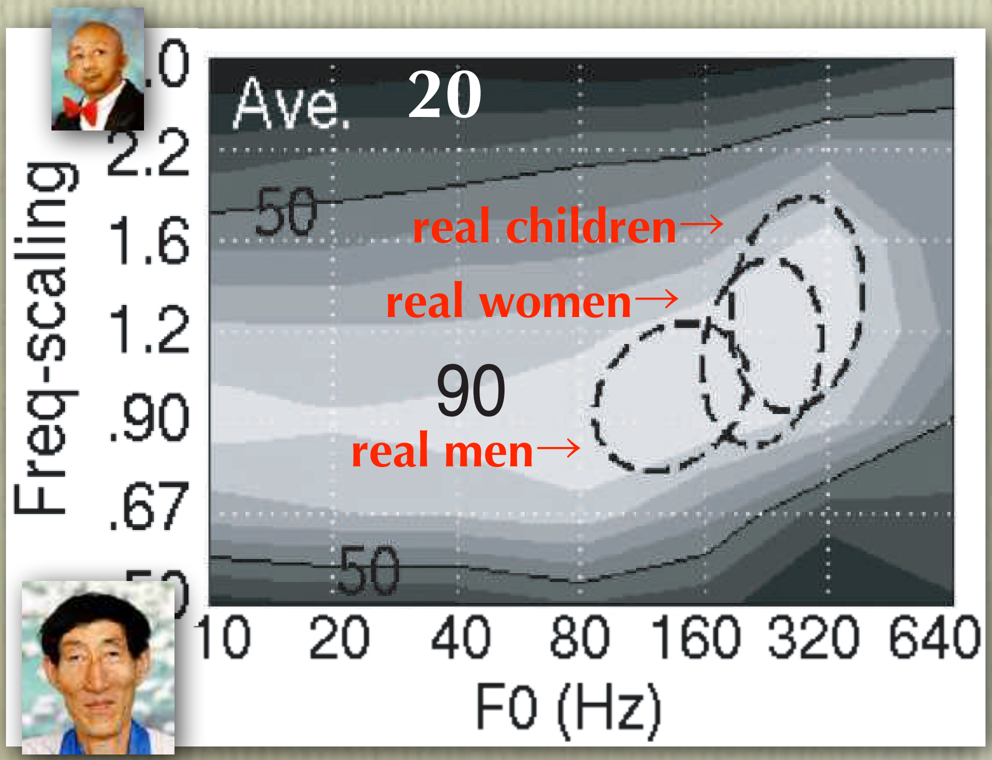
1
2

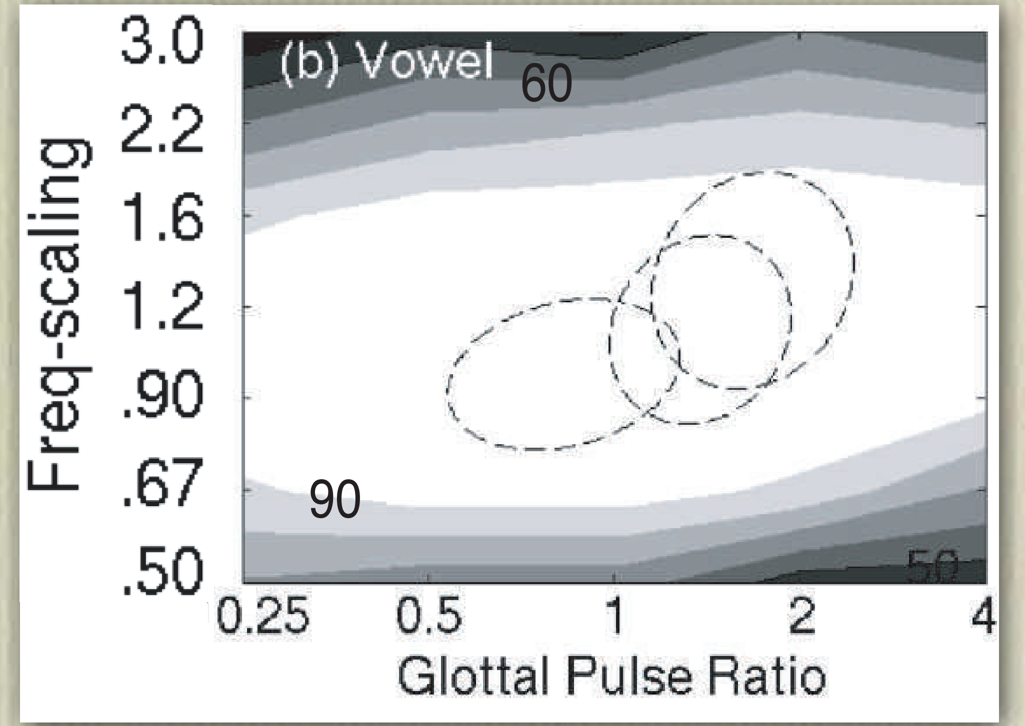

- Absolute (perfect) pitch (Do, Re, Mi... = pitch names) **(音名)**
  - 1 = So, Mi, So, Do, La, Do, Do, So. 2 = Re, Ti, Re, So, Mi, So, So, Re.
- Relative pitch with transcription ability (Do, Re... = syllable names)
  - 1 = So, Mi, So, Do, La, Do, Do, So. 2 = So, Mi, So, Do, La, Do, Do, So.

(階名)
- Relative pitch without transcription ability
  - 1 = La, La, La, La, La, La, La, La. 2 = La, La, La, La, La, La, La, La
- Different / identical tones are claimed to be identical / different.
- Not fundamental frequency (absolute property) of each tone, but it only matters **what contrast each tone has to its surrounding tones.**

What's difficult only with relative timbre?

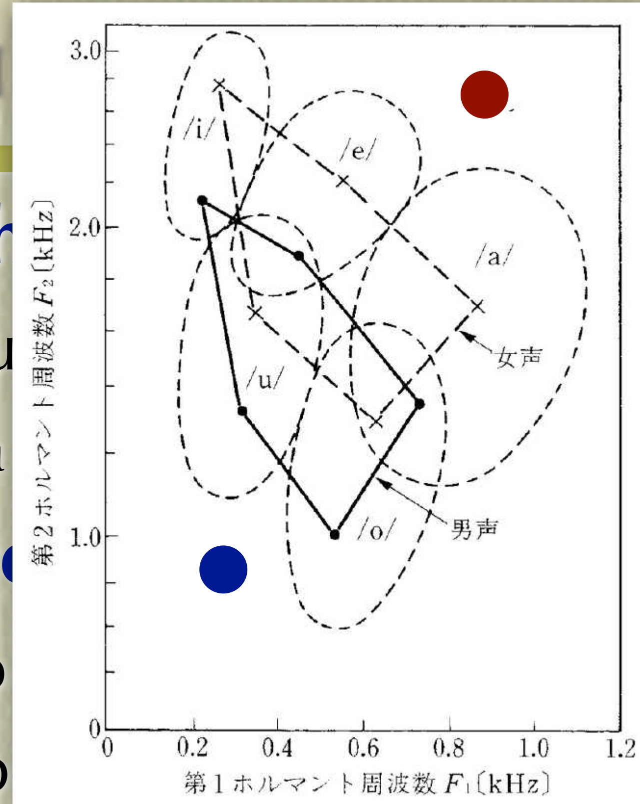
- **People with RP who can transcribe a melody cannot**
  - label a single tone using a pitch name or a syllable name.
  - Who cannot label a single speech sound (vowel sound)?
- **Identification of vowels produced by giants and fairies**
  - Difficult to label isolated vowel sounds [Aoki'04]
  - Possible to transcribe a meaningless sequence of morae [Hayashi'07]

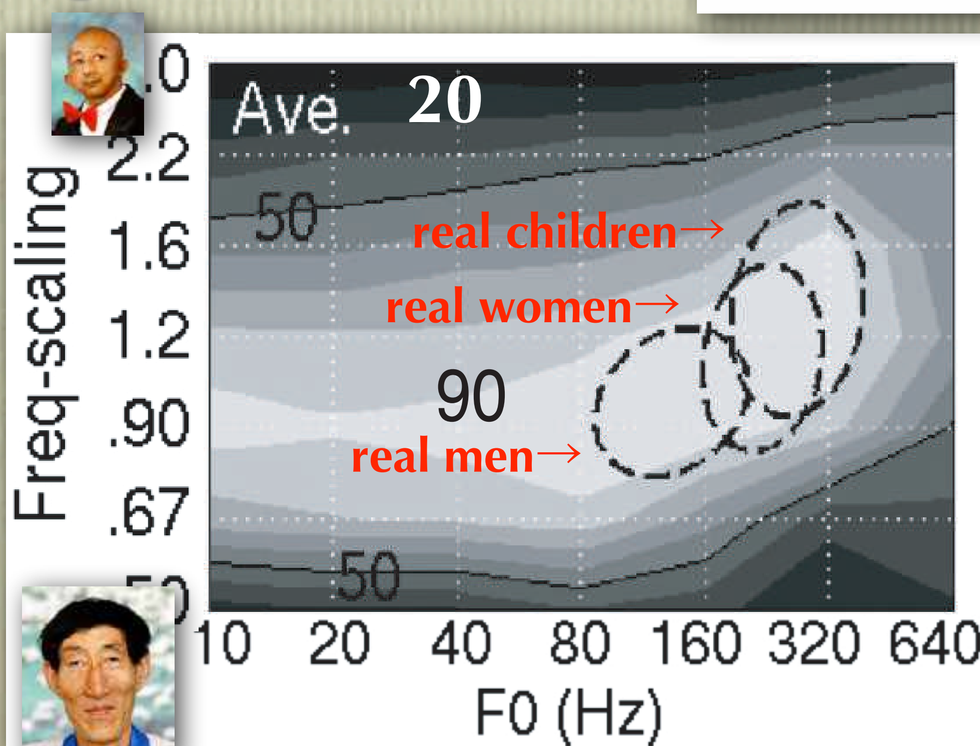


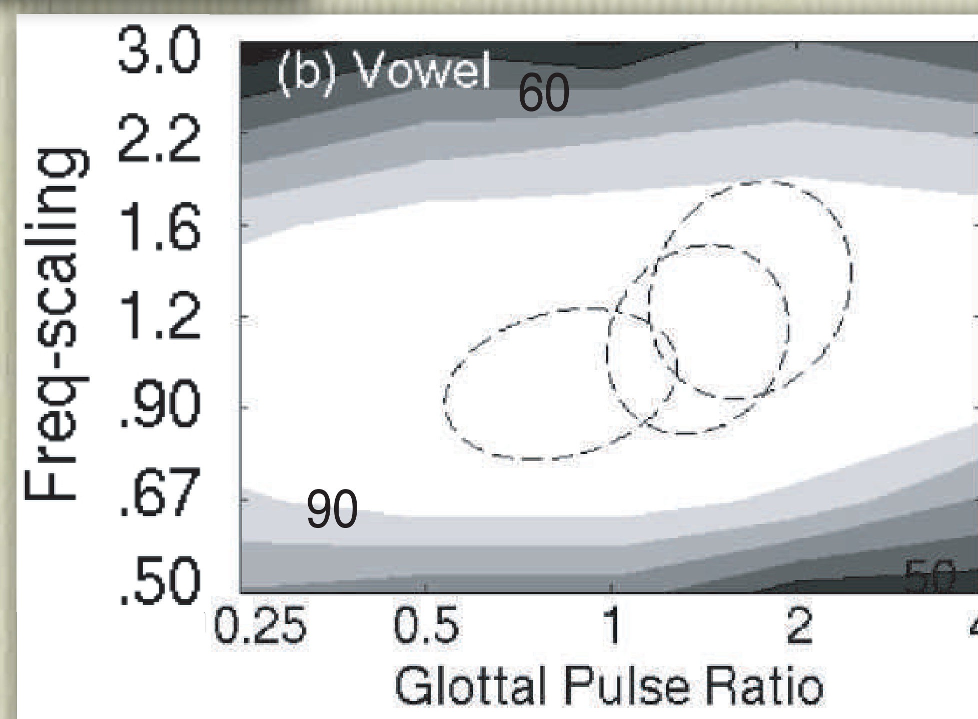


What's difficu… …elative timbre?

- **People with RP wh… …melody cannot**
  - label a single tone u… …syllable name.
  - Who cannot label a… …vowel sound)?
- **Identification of v… …giants and fairies**
  - Difficult to label iso… …ki'04]
  - Possible to transcrib… …ence of morae [Hayashi'07]

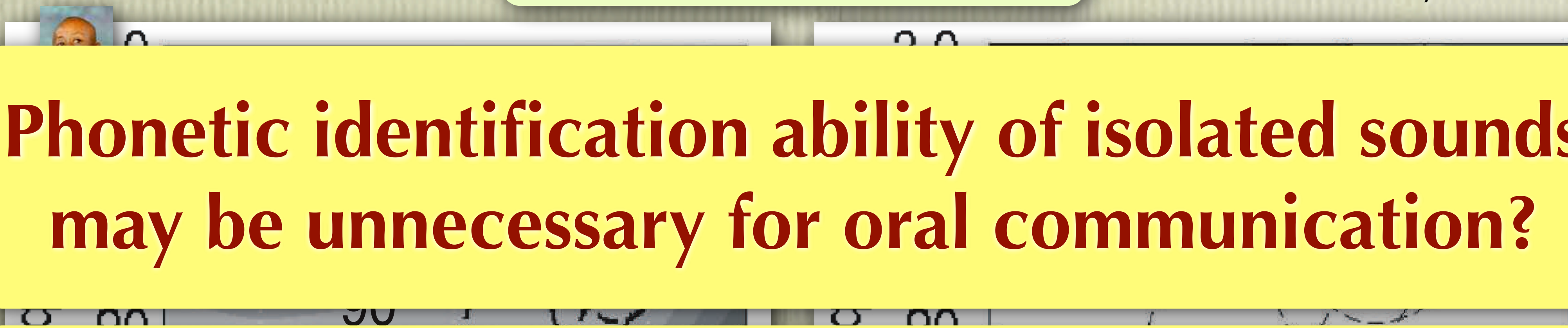






What's difficult only with relative timbre?

- People with RP w... melody cannot
  - label a single tone ... yllable name.
  - Who cannot label ... wel sound)?
- Identification of ... giants and fairies
  - Difficult to label is ... '04]
  - Possible to transcr... ce of morae [Hayashi'07]



Phonetic identification ability of isolated sounds may be unnecessary for oral communication?

Phoneme awareness is not needed for speech communication?

Invariant pitch perception against its bias

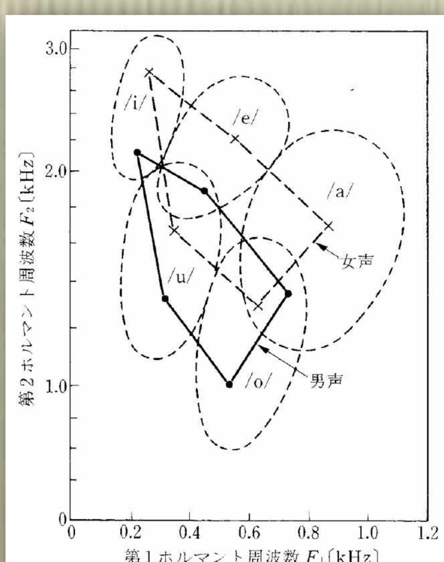
Key change (transposition) of a melody [Higashikawa'05]

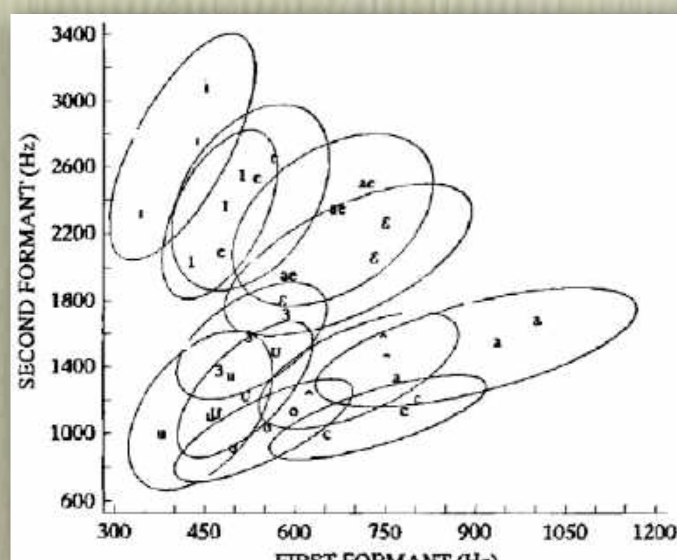
1
2

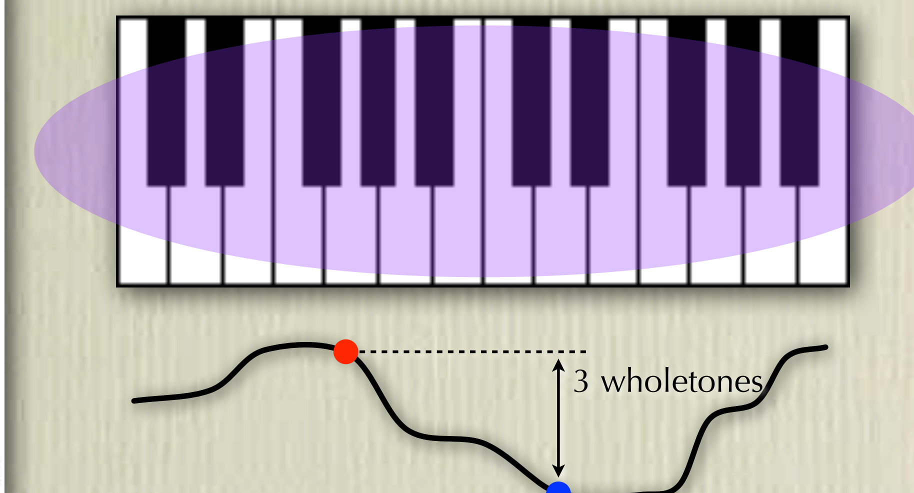
- Absolute (perfect) pitch (Do, Re, Mi... = pitch names) **(音名)**
  - 1 = So, Mi, So, Do, La, Do, Do, So. 2 = Re, Ti, Re, So, Mi, So, So, Re.
- Relative pitch with transcription ability (Do, Re... = syllable names)
  - 1 = So, Mi, So, Do, La, Do, Do, So. 2 = So, Mi, So, Do, La, Do, Do, So. **(階名)**
- Relative pitch without transcription ability
  - 1 = La, La, La, La, La, La, La, La. 2 = La, La, La, La, La, La, La, La
- Different / identical tones are claimed to be identical / different.
- Not fundamental frequency (absolute property) of each tone, but it only matters **what contrast each tone has to its surrounding tones.**

Another difficult task for RP listeners

- **Difficult task for those who cannot transcribe a melody**
  - Keep the third *tone* in a given melody in mind. Then, raise your hand if you find the same *tone* in a new melody.
    - If symbolic labeling is difficult, this task is very difficult.
- **Difficult task for the speech version of these people**
  - Keep the third *sound* in a given utterance in mind. Then, raise your hand if you find the same *sound* in a new utterance.
    - If symbolic labeling is difficult, this task is very difficult.







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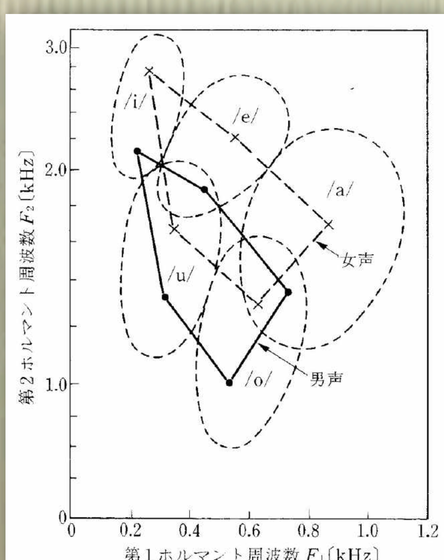
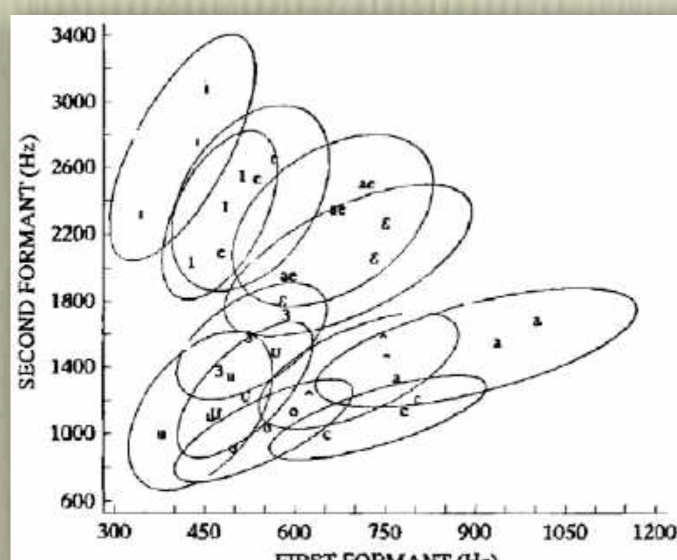
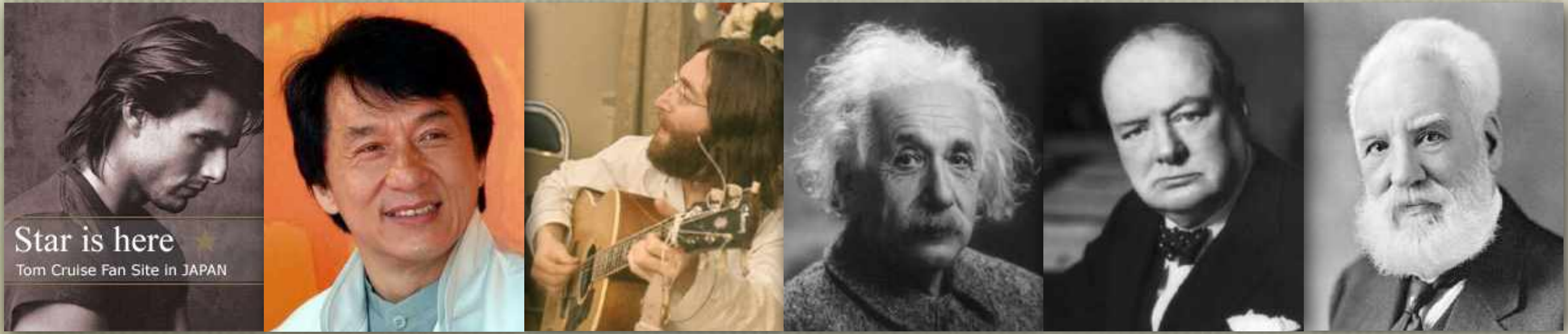




In E-speaking countries, there have to be people who have severe troubles in reading and writing?

Another difficult task for RP listeners

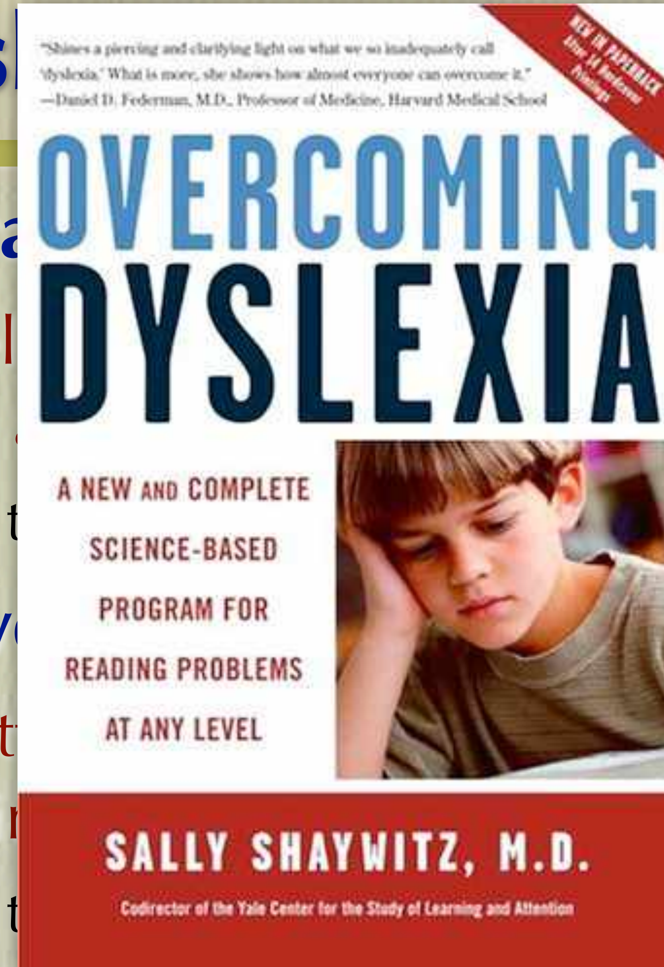
- **Difficult task for those who cannot transcribe a melody**
  - Keep the third *tone* in a given melody in mind. Then, raise your hand if you find the same *tone* in a new melody.
    - If symbolic labeling is difficult, this task is very difficult.
- **Difficult task for the speech version of these people**
  - Keep the third *sound* in a given utterance in mind. Then, raise your hand if you find the same *sound* in a new utterance.
    - If symbolic labeling is difficult, this task is very difficult.

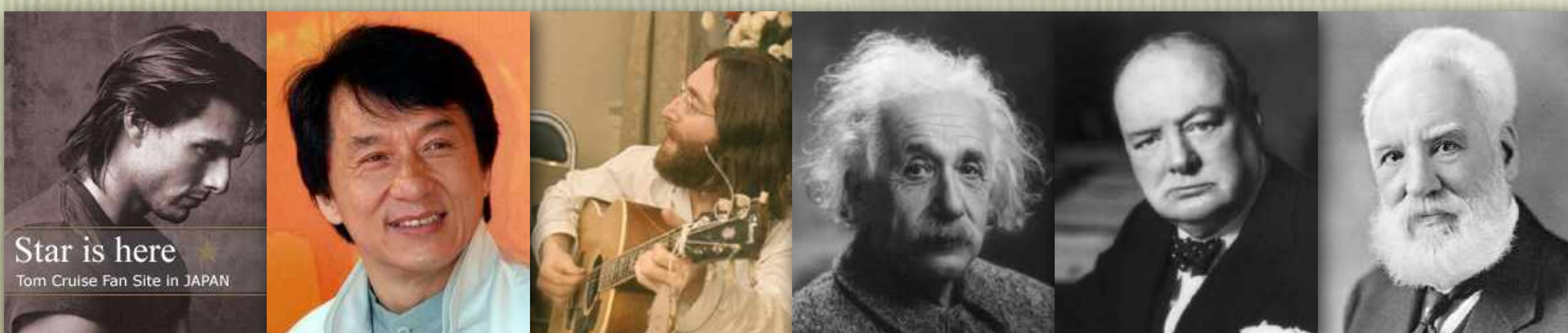


Dyslexia (phonological dyslexia)

Ar… t tas… ers

- **Diffic… who ca… melody**
  - Keep… en mel… e your hanc… *one* in …
    - If s… lt, this t…
- **Diffic… ech v… ple**
  - Keep… ven ut… raise your hanc… *ound* ir…
    - If s… lt, this t…





Dyslexia (phonological dyslexia)

How I encountered dyslexia.

「あ」という声を聞いて母音「あ」と同定する能力は音声言語運用に必要か？

——音声認識研究からの一つの提言——

第4章 話し言葉の音声

峯松 信明

はじめに ～何、この変なタイトル？～

タイトルを見て、多くの読者が首を傾げていることだろう。しかし、十一頁の本記事を読み終えた時に、ほぼ全ての読者に私の意図は通じるもの、と考えている。そう。「「あ」という声を聞いて、それを有限個の音カテゴリの一つとしての母音「あ」であると同定する能力は、音声言語運用の必要条件ではない。」との主張を本稿では展開する（文献1）（文献2）。

そんな馬鹿な、と思われるかもしれない。こんな実験を考えてみよう。身長300cmの巨人と50cmの小人に孤立母音を発声してもらう。通常音声学の教科書には、F_1・F_2の母音図が出ている（図1参照）。複数の男性／女性のサンプルから、凡そ男性の各母音はこの領域、女性の各母音はこの領域にある、といった図である。フォルマント周波数（共鳴周波数）は声道長に依存するため、身長が50cm、300cmという架空の大人を想定した場合、彼らの母音は、通常知られている領域の外に存在する。そのような母音でも、現在の音声分析・再合成技術を使えば非常に高品質な音声として生成できる。さて、聞いたことのない母音音声を孤立提示されて、読者は同定できるだろうか？

文献(5)によれば、これは困難なタスクであることが分かる。しかし、その巨人、小人が無意味モーラ列を単

「音声言語は流暢だし雄弁。頭は良いのかもしれない。でも何故か本が読めない、手紙が書けない。そういう成人が米国や英国に多かったりしませんか？　え〜と、教育を受けていないとか、そういう事ではなく、彼らの認知特性として文字言語が何故か難しい……」

「先生、ディスレクシアってご存知なんですか？　特に音韻性のやつ。」

「でぃすれ……何ですかそれ？」

「変だな。先生、今、自分でディスレクシアの説明してたじゃないですか。」

四一年間の人生の中で、あれほど口をあんぐり開けたことは無い。顎が外れるかと思った。これは実話である。

私は彼ら（文献15）の存在を、音声の物理学に基づいて予言していた。

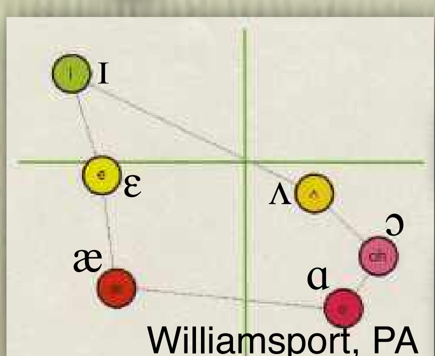
日本語学4月号，p.187-197，
明治書院(2008)

"Separately brought up identical twins"

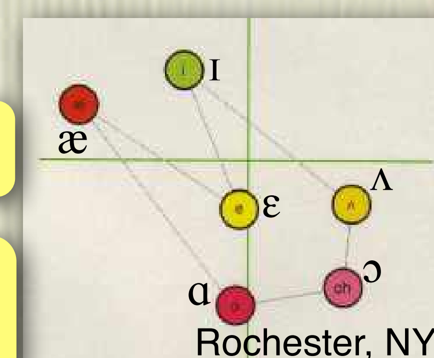
The parents get divorced immediately after the birth.

- The twins were brought up separately by the parents.
- What kind of pron. will the twins have acquired 5 years later?

Diff. of VTL = Diff. of timbre



Diff. of regional accents = Diff. of timbre

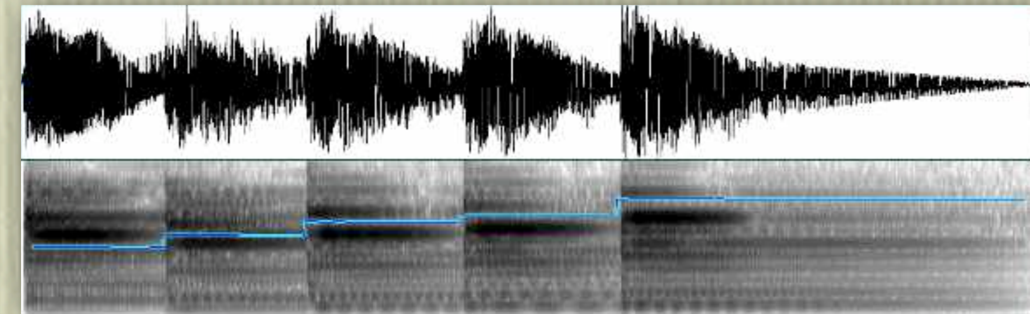


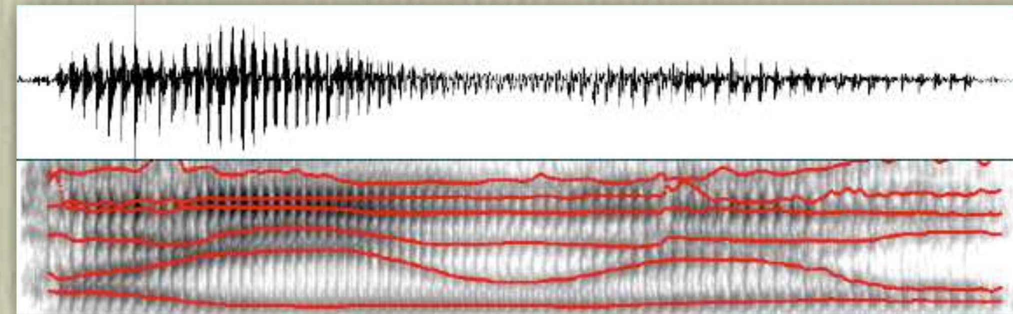
Machines that don't learn what infants don't learn.

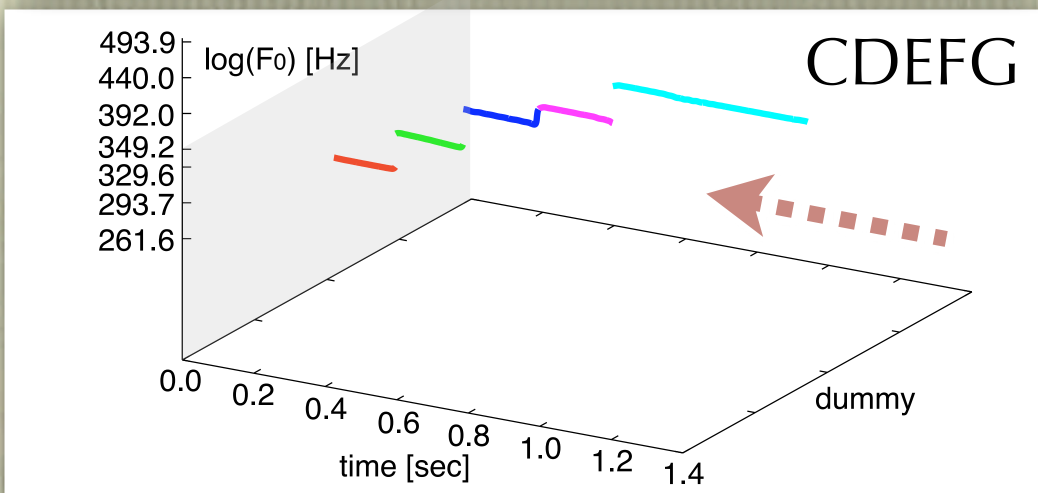
Menu of the last four lectures

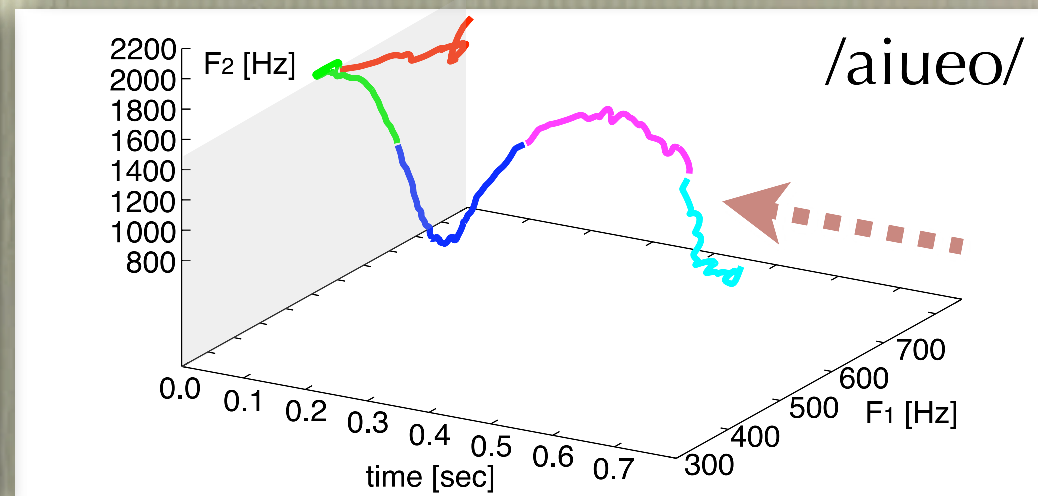
- **Robust processing of easily changeable stimuli**
  - Robust processing of general sensory stimuli
  - Any difference in the processing between humans and animals?
- **Human development of spoken language**
  - Infants' vocal imitation of their parents' utterances
  - What acoustic aspect of the parents' voices do they imitate?
- **Speaker-invariant holistic pattern in an utterance**
  - Completely transform-invariant features -- *f*-divergence --
  - Implementation of word Gestalt as relative timbre perception
  - Application of speech structure to robust speech processing
- **Radical but interesting discussion**
  - An interesting link to some behaviors found in language disorder
  - An interesting thought experiment

Relative pitch vs. relative timbre



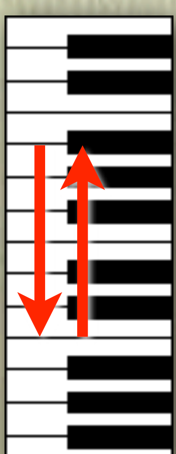




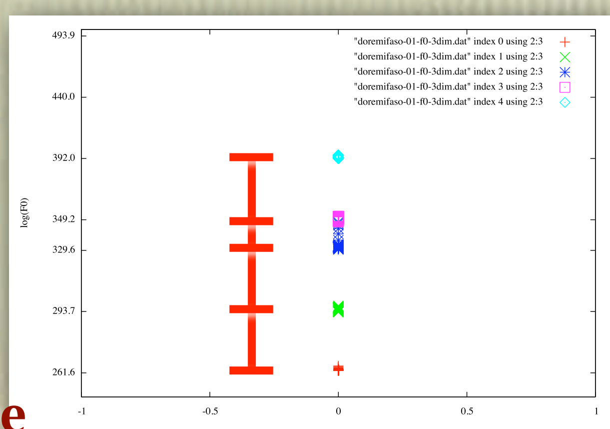


pitch modulation

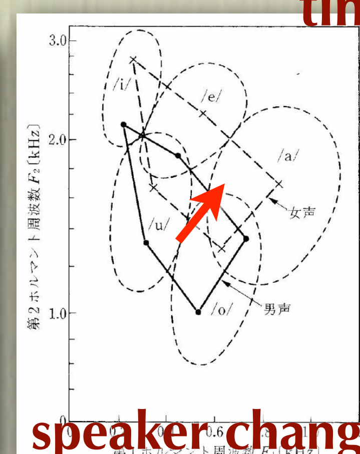
timbre modulation



log(F0)

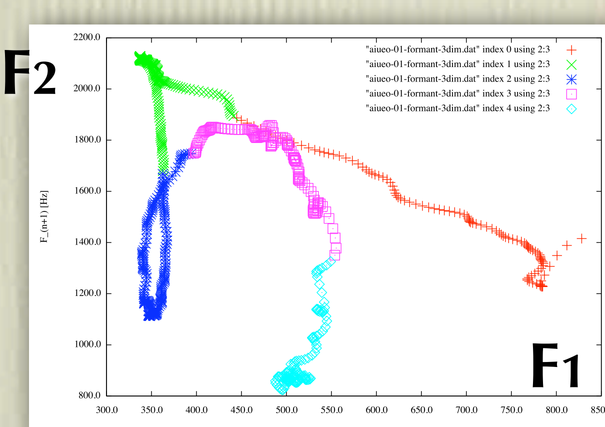


key change

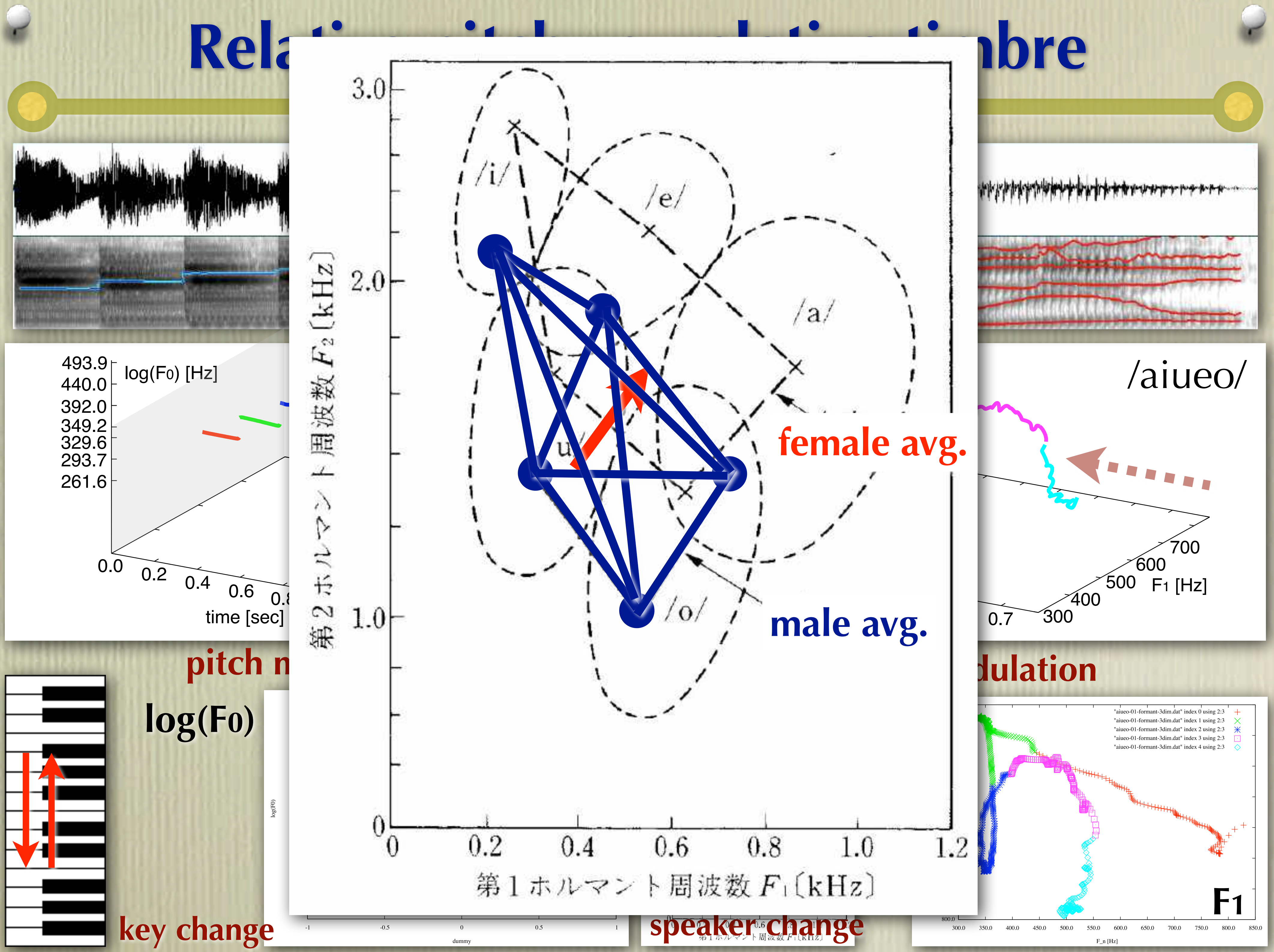


speaker change

F2



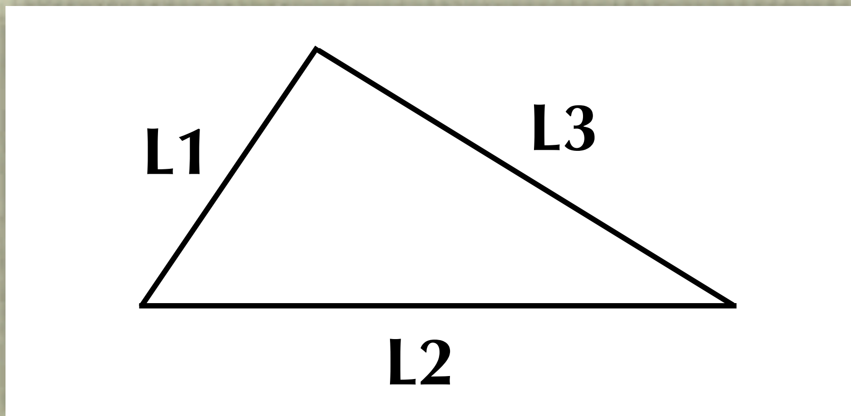
F1



Rela
mbre
3.0
2.0
1.0
0
0.2
0.4
0.6
0.8
1.0
1.2
第2ホルマント周波数 F₂ [kHz]
第1ホルマント周波数 F₁ [kHz]
/i/
/e/
/a/
/u/
/o/
female avg.
male avg.
493.9
440.0
392.0
349.2
329.6
293.7
261.6
log(F0) [Hz]
0.0
0.2
0.4
0.6
time [sec]
/aiueo/
700
600
500
400
300
F1 [Hz]
0.7
pitch m
dulation
log(F0)
key change
speaker change
F1

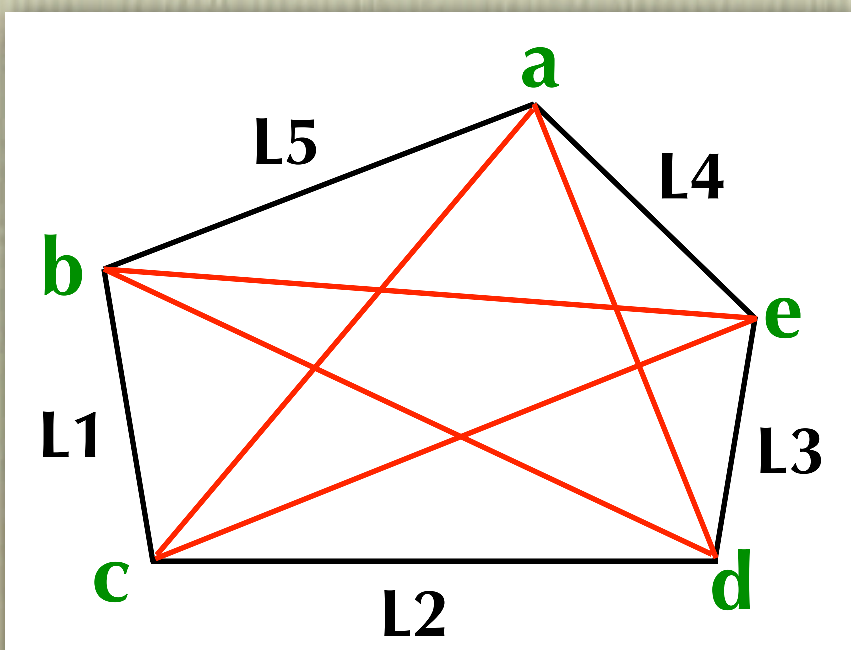
Definition of the shape of a thing

Triangle



(L1, L2, L3)

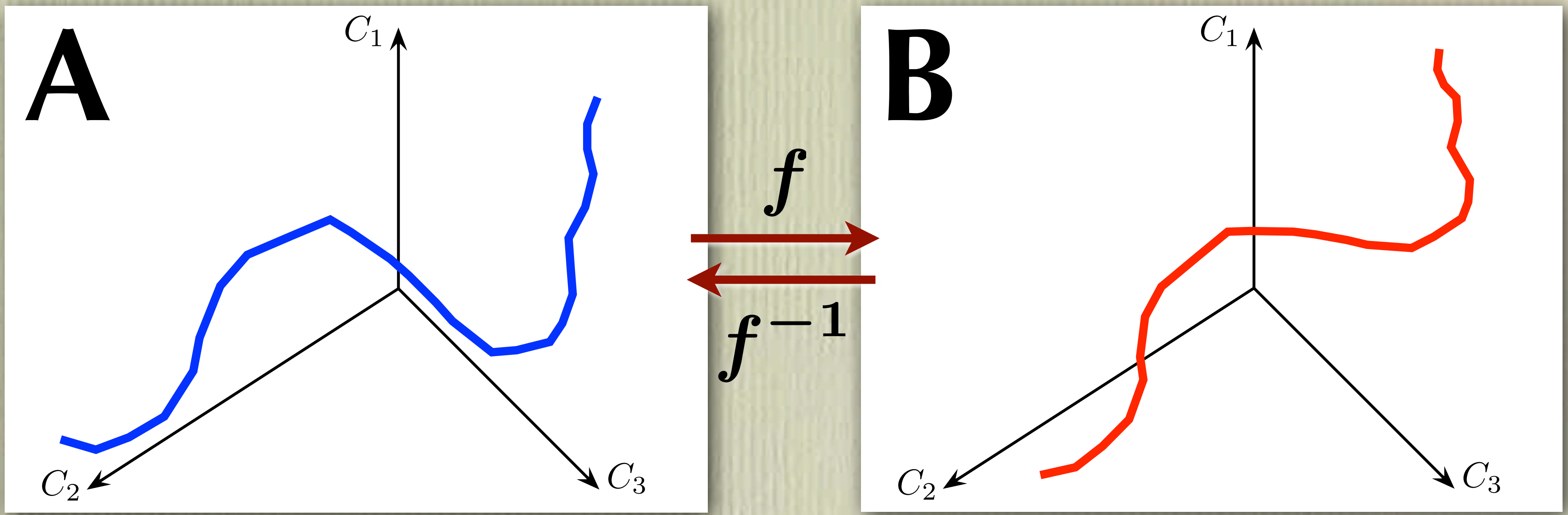
N-point general geometrical structure



$$
\begin{array}{c c}
 & \begin{array}{cccc} \mathbf{a} & \mathbf{b} & & \mathbf{e} \end{array} \\
\begin{array}{c} \mathbf{a} \\ \mathbf{b} \\ \mathbf{c} \\ \mathbf{d} \\ \mathbf{e} \end{array} &
\begin{bmatrix}
d_{11} & d_{12} & \cdots & d_{1N} \\
d_{21} & d_{22} & \cdots & d_{2N} \\
d_{31} & & & \\
\vdots & & & \\
d_{N1} & d_{N2} & \cdots & d_{NN}
\end{bmatrix}
\end{array}
$$

Math. modeling of speaker variability

- **Speaker difference = mapping of a voice space**
  - Space of speaker A $\leftrightarrow$ space of speaker B

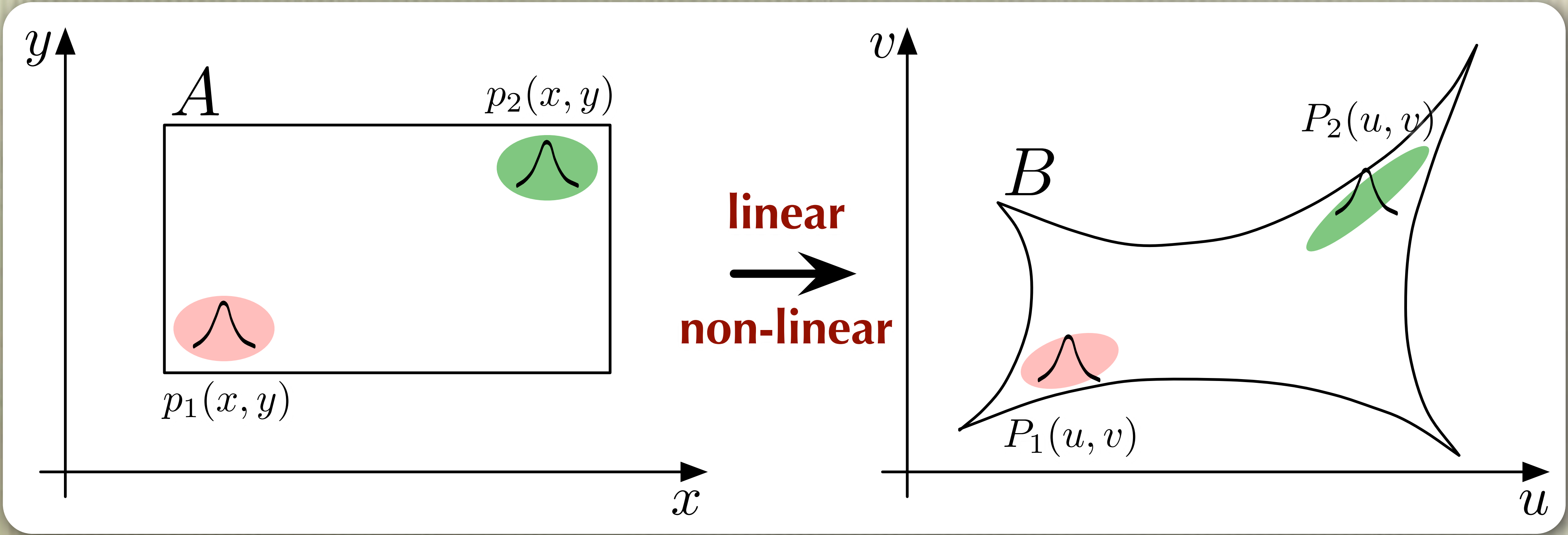


- **Mapping of speaker A into any of 7 billion speakers**
  - 7 billion x 7 billion transformations are possible.
  - Truly speaker-independence = mapping-invariant contrasts
    - **Are there any contrastive features that are invariant with any mapping?**

Complete transform-invariance

Complete invariance between two spaces

- An assumption
  - The transform is convertible and differentiable anywhere.
- An event in a space should be represented as distribution.
  - Event p in space A is transformed into event P in space B
  - p and P are physically different (/a/ of speaker A and /a/ of speaker B)



Complete transform-invariance

Variable conversion and integral

- A single variable: $x = x(t) \quad (x_1 = x(t_1), x_2 = x(t_2))$

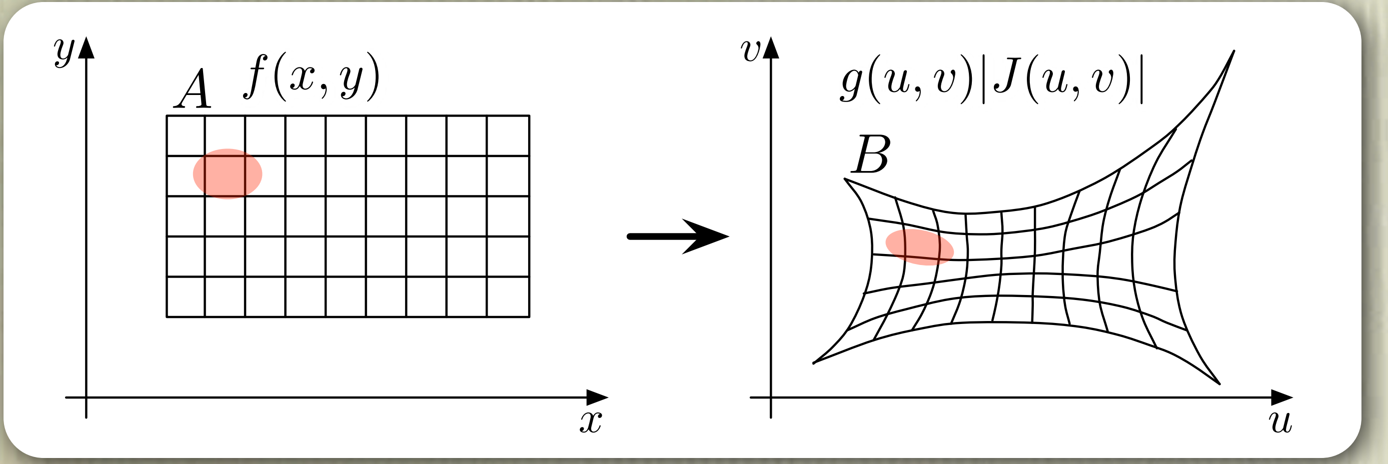
$$\int_{x_1}^{x_2} f(x)dx = \int_{t_1}^{t_2} f(x(t))\frac{dx(t)}{dt}dt = \int_{t_1}^{t_2} g(t)x'(t)dt$$

- Two variables: $x = x(u,v), \;\; y = y(u,v)$

$$\begin{aligned} x &= 3u + 2v - 5 \\ y &= 4u + 5v + 3 \end{aligned}$$

$$\iint_A f(x,y)dxdy = \iint_B f(x(u,v), y(u,v))|J(u,v)|dudv$$

$$= \iint_B g(u,v)|J(u,v)|dudv \qquad J(u,v) \equiv \frac{\partial(x,y)}{\partial(u,v)} \equiv \det\begin{bmatrix} \frac{\partial x}{\partial u} & \frac{\partial x}{\partial v} \\ \frac{\partial y}{\partial u} & \frac{\partial y}{\partial v} \end{bmatrix}$$



Complete transform-invariance

Variable conversion and probability density function

- A single variable: $x = x(t) \quad (x_1 = x(t_1), x_2 = x(t_2))$

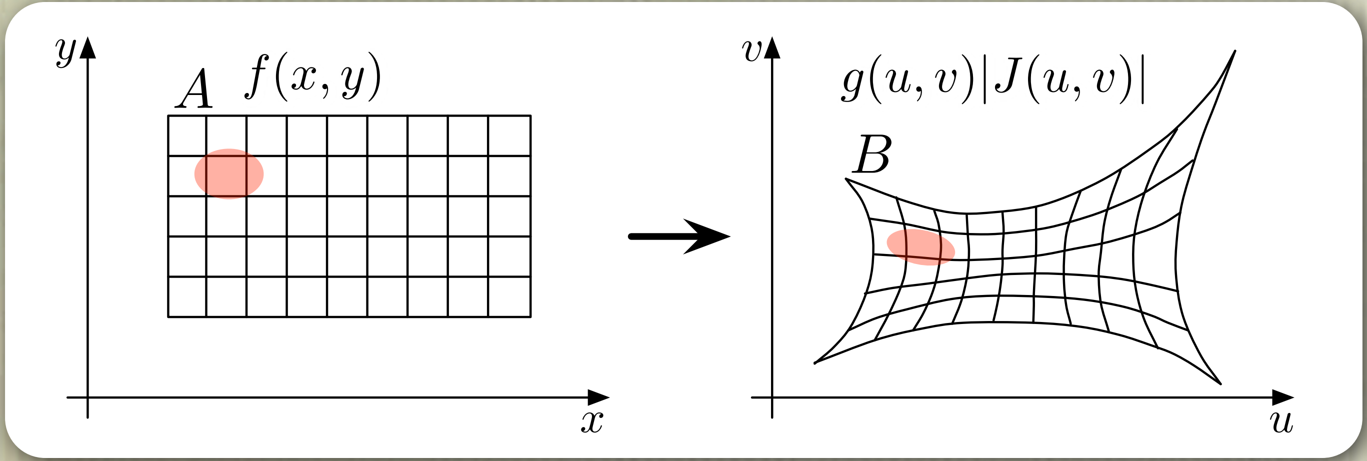
$$1.0 = \int_{x_1}^{x_2} p(x)dx = \int_{t_1}^{t_2} p(x(t))\frac{dx(t)}{dt}dt = \int_{t_1}^{t_2} \underline{q(t)x'(t)}dt$$

- Two variables: $x = x(u,v),\ \ y = y(u,v)$

$$\begin{aligned} x &= 3u + 2v - 5 \\ y &= 4u + 5v + 3 \end{aligned}$$

$$1.0 = \iint_A f(x,y)dxdy = \iint_B f(x(u,v),y(u,v))|J(u,v)|dudv$$

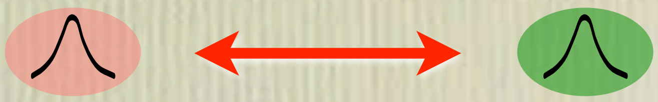
$$= \iint_B g(u,v)|J(u,v)|dudv \qquad J(u,v) \equiv \frac{\partial(x,y)}{\partial(u,v)} \equiv \det\begin{bmatrix} \frac{\partial x}{\partial u} & \frac{\partial x}{\partial v} \\ \frac{\partial y}{\partial u} & \frac{\partial y}{\partial v} \end{bmatrix}$$



Complete transform-invariance

Bhattacharyya distance

- One of the distance measures bet. two distributions
- $x = x(u, v), \;\; y = y(u, v)$
- $BD(p_1(x, y), p_2(x, y))$



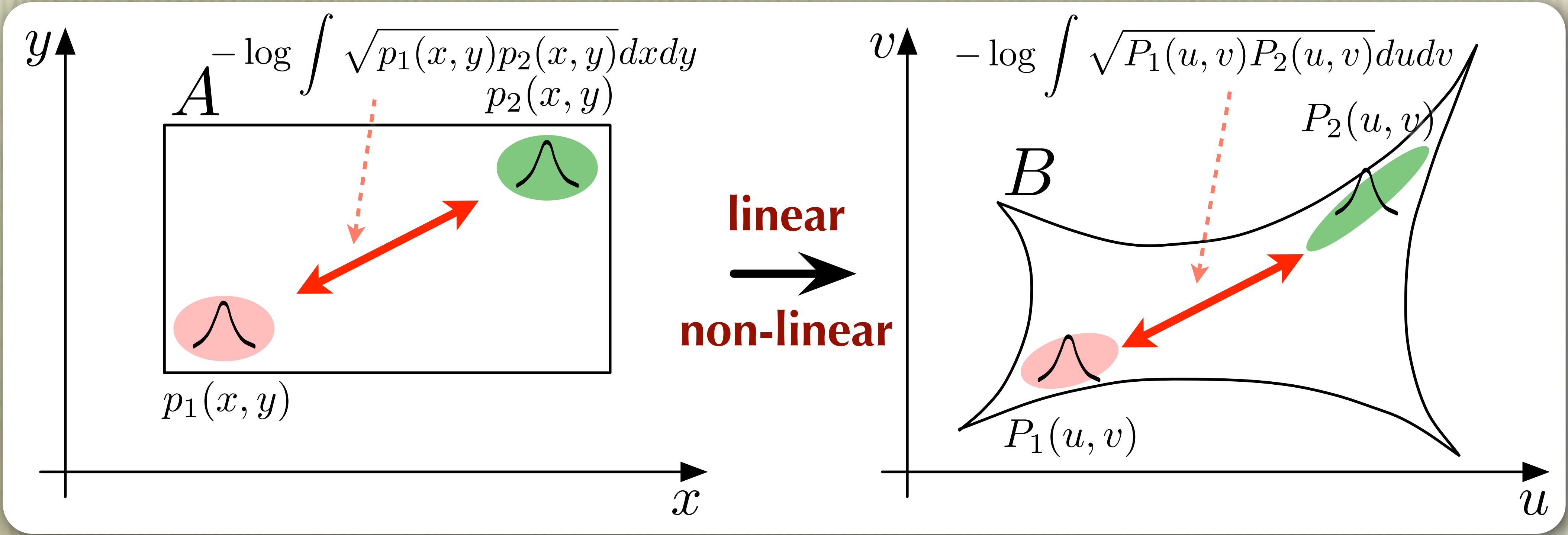
$$
\begin{aligned}
&= -\log \iint \sqrt{p_1(x, y) p_2(x, y)}\, dx dy \\
&= -\log \iint \sqrt{q_1(u, v) q_2(u, v)} |J(u, v)| dx dy \\
&= -\log \iint \sqrt{q_1(u, v)|J(u, v)| \cdot q_2(u, v)|J(u, v)|}\, du dv \\
&= -\log \iint \sqrt{P_1(u, v) P_2(u, v)}\, du dv \\
&= BD(P_1(u, v), P_2(u, v))
\end{aligned}
$$

$q_1(u, v) = p_1(x(u, v), y(u, v)), \qquad J = \text{Jacobian}$

Complete transform-invariance

Complete invariance between two spaces

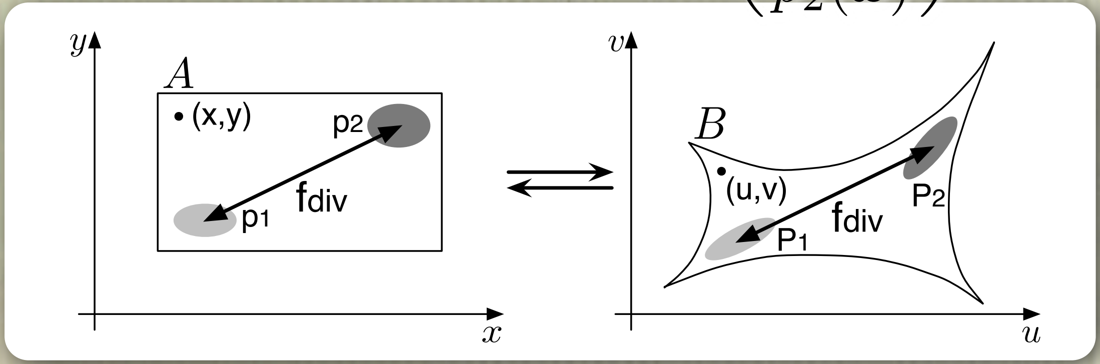
- An assumption
  - The transform is convertible and differentiable anywhere.
- An event in a space should be represented as distribution.
  - Event p in space A is transformed into event P in space B
  - p and P are physically different (/a/ of speaker A and /a/ of speaker B)



Complete transform-invariance

Any general expression for invariance? [Qiao'10]

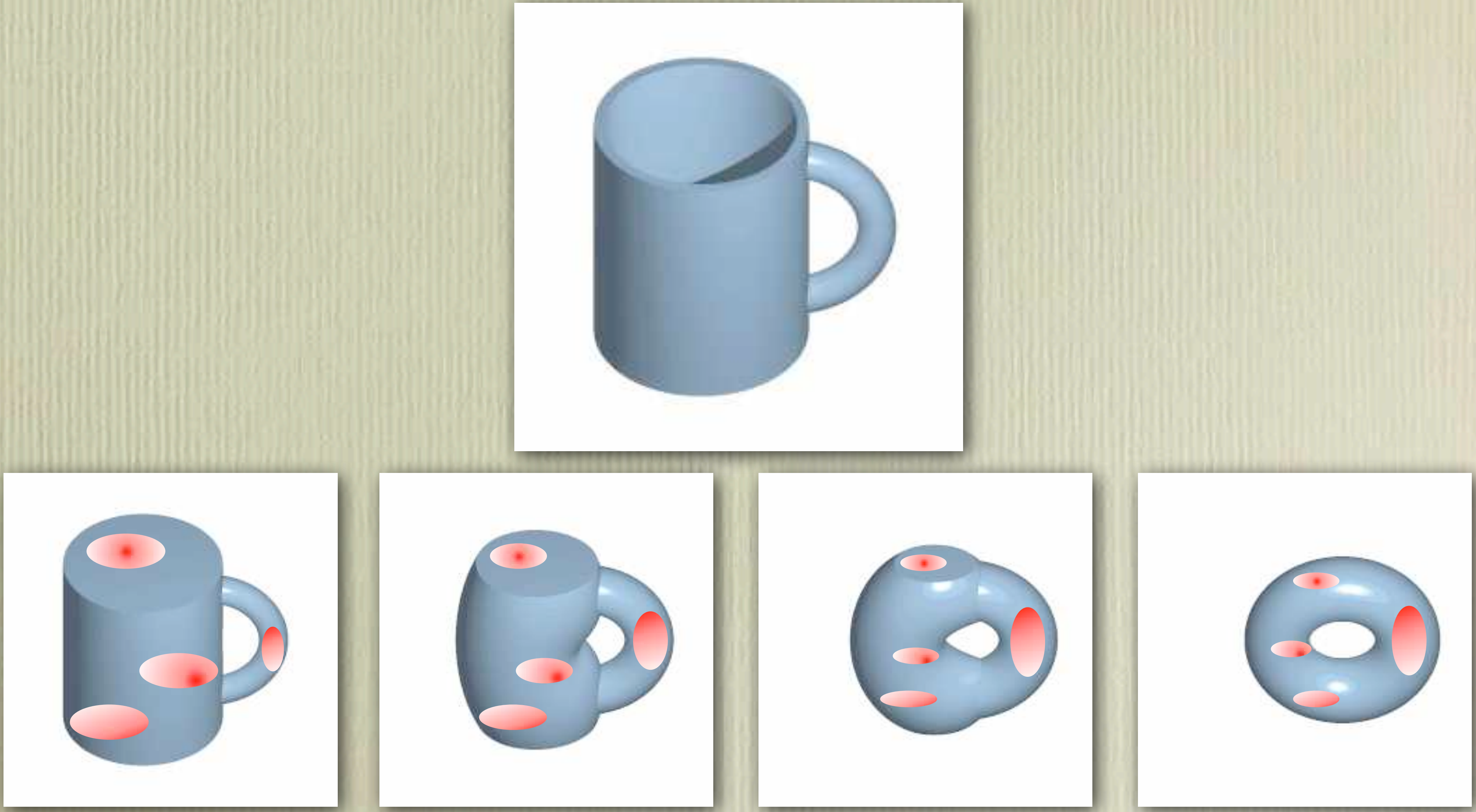
- BD is just one example of invariant contrasts.
- f-divergence is invariant with any kind of transformation.
  - $f_{div}(p_1, p_2) = \int p_2(\boldsymbol{x}) g\left(\frac{p_1(\boldsymbol{x})}{p_2(\boldsymbol{x})}\right) d\boldsymbol{x}$
  - $g(t) = t\log(t) \rightarrow f_{div} = \mathrm{KL} - \mathrm{div}.$ $\quad g(t) = \sqrt{t} \rightarrow -\log(f_{div}) = \mathrm{BD}$
  - $f_{div}(p_1, p_2) = f_{div}(P_1, P_2)$
- Invariant features have to be f-divergence.
  - If $\int M(p_1(\boldsymbol{x}), p_2(\boldsymbol{x}))d\boldsymbol{x}$ is invariant with any transformation,
  - M has to be in the form of $M = p_2(\boldsymbol{x}) g\left(\frac{p_1(\boldsymbol{x})}{p_2(\boldsymbol{x})}\right)$



Invariance in variability

Topological invariance [Minematsu'09]

- Topology focuses on invariant features wrt. any kind of deformation.



Invariance in variability

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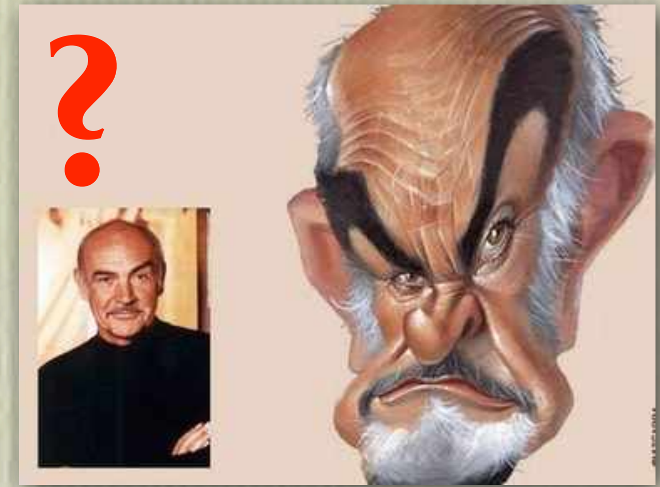
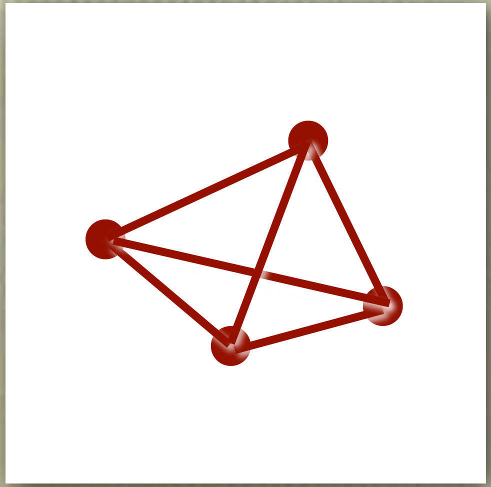
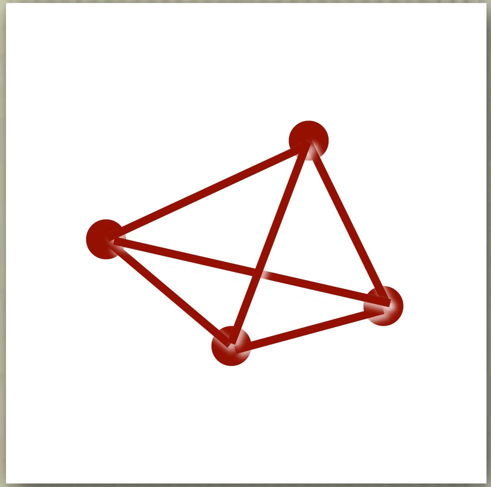
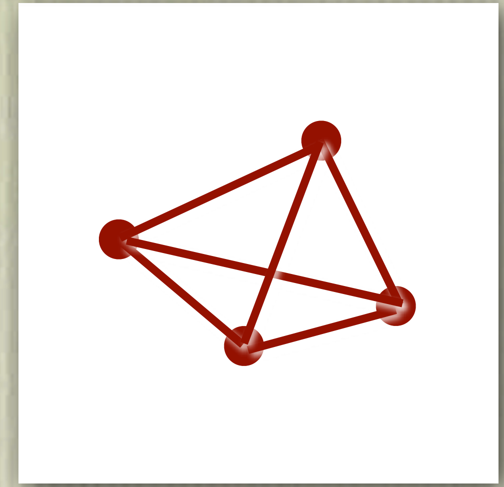
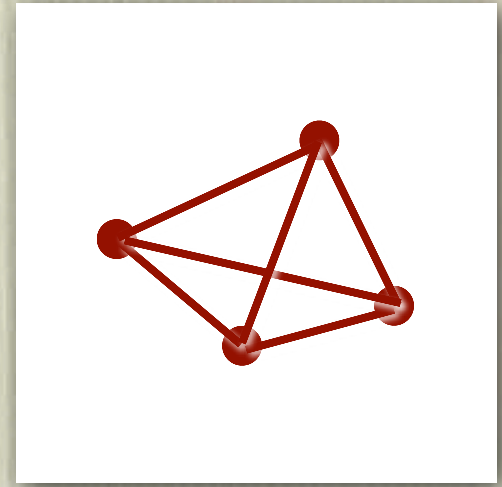




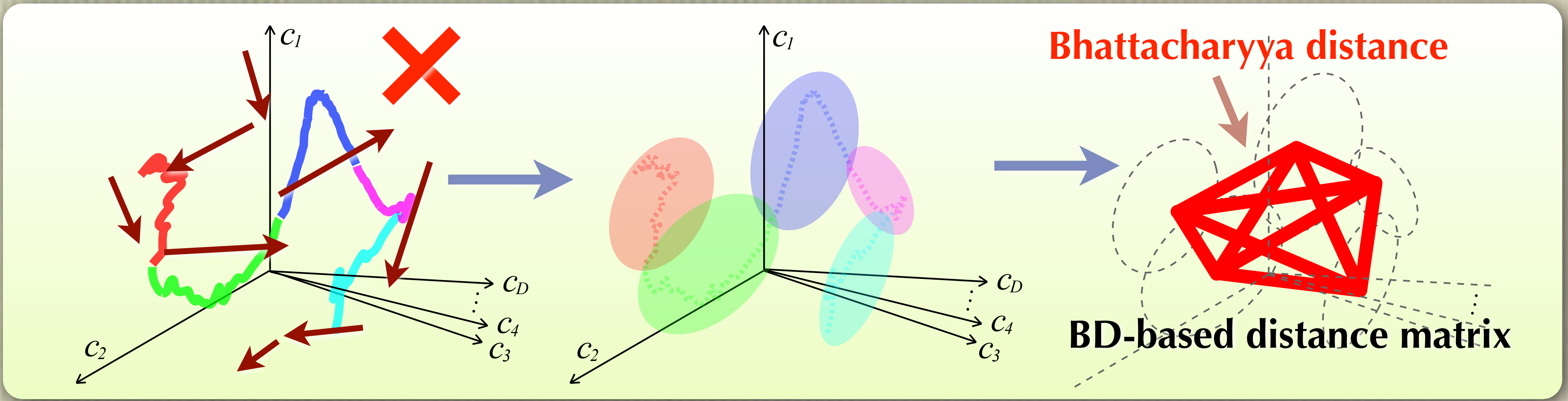


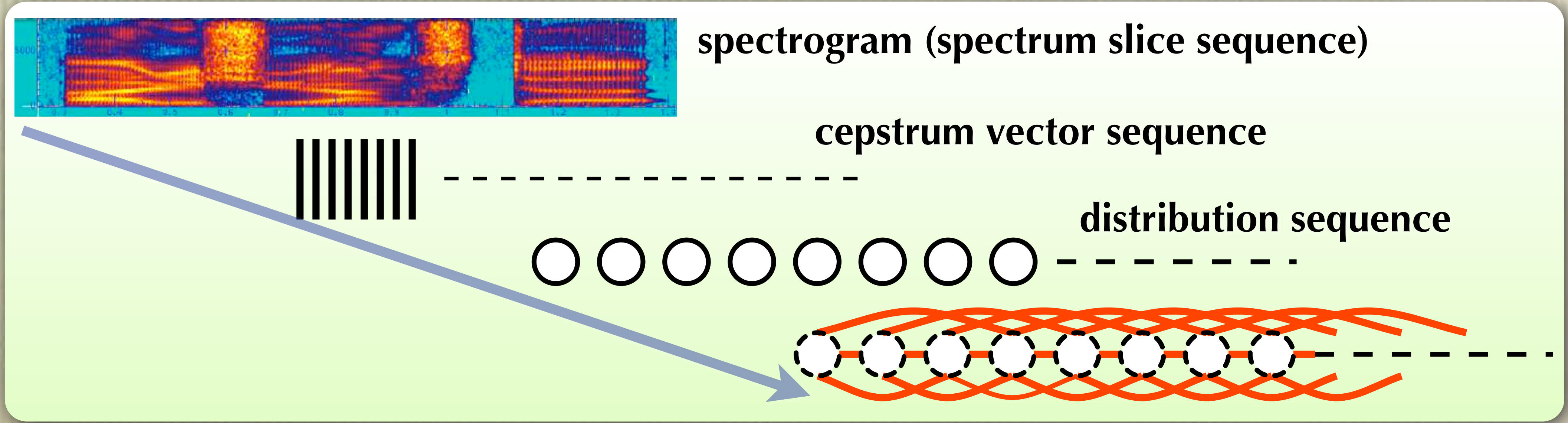




Invariant speech structure

Utterance to structure conversion using *f*-div. [Minematsu'06]





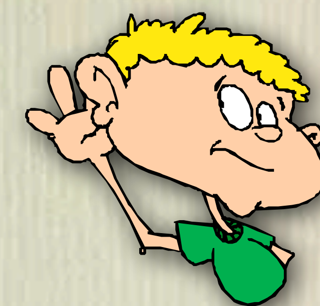
- An event (distribution) may be smaller than a phoneme.

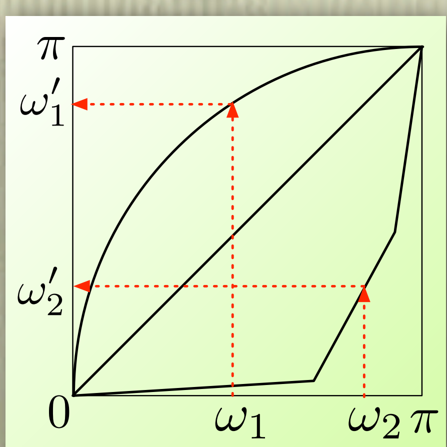
Speech modification by VTLD

Speech modification by non-linguistic factors

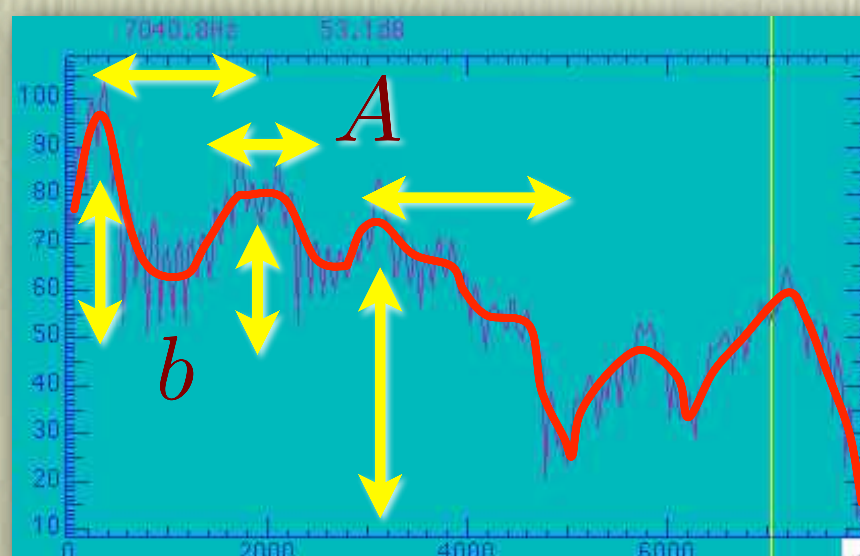
$\times H(s)$

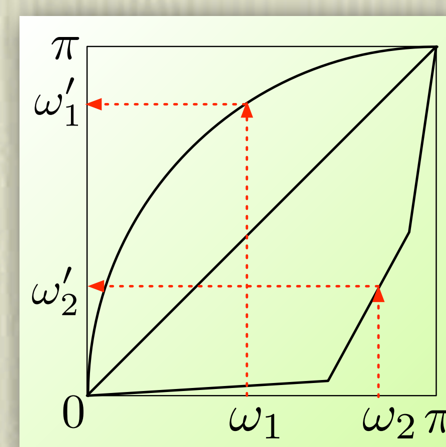
$c' = c + b$





$c' = Ac$

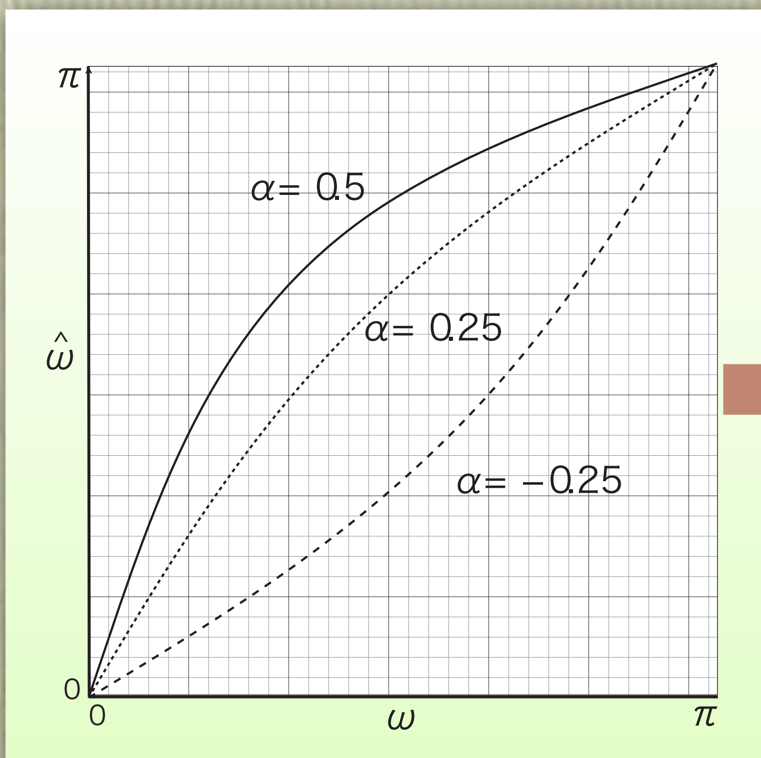




$c' = Ac$

VTL-based variation = × matrix A

- **Vocal tract length variation**
  - Can be approximated as multiplication of matrix A in cep. domain.
- **A is represented as warping parameter α.**



$$\hat{\boldsymbol{c}} = (\hat{c}_1\ \hat{c}_2\ \hat{c}_3\ \hat{c}_4 \cdots)^t$$

$$\boldsymbol{A} = \begin{pmatrix} 1-\alpha^2 & 2\alpha-2\alpha^3 & \cdots & \cdots \\ -\alpha+\alpha^3 & 1-4\alpha^2+3\alpha^4 & \cdots & \cdots \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \end{pmatrix}$$

$$\boldsymbol{c} = (c_1\ c_2\ c_3\ c_4 \cdots)^t.$$

$$a_{ij} = \frac{1}{(j-1)!} \sum_{m=\max(0,j-i)}^{j} \binom{j}{m} \times \frac{(m+i-1)!}{(m+i-j)!} (-1)^m \alpha^{(2m+i-j)}$$

$$\hat{z}^{-1} = \frac{z^{-1}-\alpha}{1-\alpha z^{-1}}, \quad z = e^{j\omega}, \quad \hat{z} = e^{j\hat{\omega}}$$

$$\boldsymbol{c}' = \boldsymbol{A}\boldsymbol{c}$$

Geometrical characteristics of A

$$\begin{pmatrix} \hat{c}_1 \\ \hat{c}_2 \end{pmatrix} = \underbrace{\begin{pmatrix} 1-\alpha^2 & 2\alpha-2\alpha^3 \\ -\alpha+\alpha^3 & 1-4\alpha^2+3\alpha^4 \end{pmatrix}}_{T} \begin{pmatrix} c_1 \\ c_2 \end{pmatrix}$$

$$\boldsymbol{T} = \boldsymbol{R} + \boldsymbol{O}$$

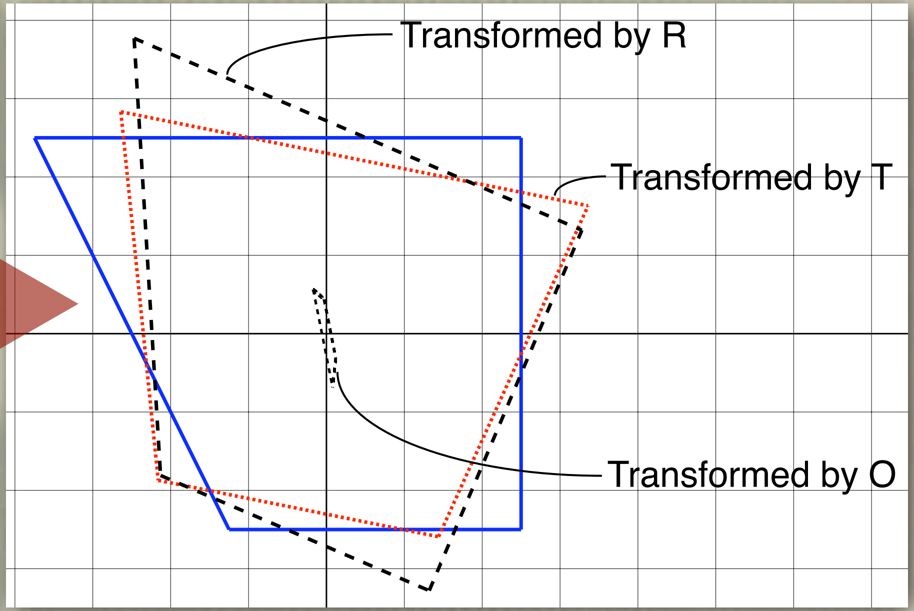
$$\boldsymbol{R} = \begin{pmatrix} 1-2\alpha^2 & 2\alpha(1-\frac{1}{2}\alpha^2) \\ -2\alpha(1-\frac{1}{2}\alpha^2) & 1-2\alpha^2 \end{pmatrix}$$

$$\boldsymbol{O} = \begin{pmatrix} \alpha^2 & -\alpha^3 \\ -\alpha & -2\alpha^2+3\alpha^4 \end{pmatrix}.$$

$$\boldsymbol{R} \simeq \begin{pmatrix} 1-2\alpha^2 & 2\alpha\sqrt{1-\alpha^2} \\ -2\alpha\sqrt{1-\alpha^2} & 1-2\alpha^2 \end{pmatrix}$$

$$= \begin{pmatrix} \cos 2\theta & \sin 2\theta \\ -\sin 2\theta & \cos 2\theta \end{pmatrix} \quad (\alpha = \sin\theta)$$

$$\boldsymbol{A} = \begin{pmatrix} 1-\alpha^2 & 2\alpha-2\alpha^3 & \cdots & \cdots \\ -\alpha+\alpha^3 & 1-4\alpha^2+3\alpha^4 & \cdots & \cdots \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \end{pmatrix}$$



Is it the case in N dimensions?

Geometrical characteristics of A

What is the rotation matrix in an N dimensional space?

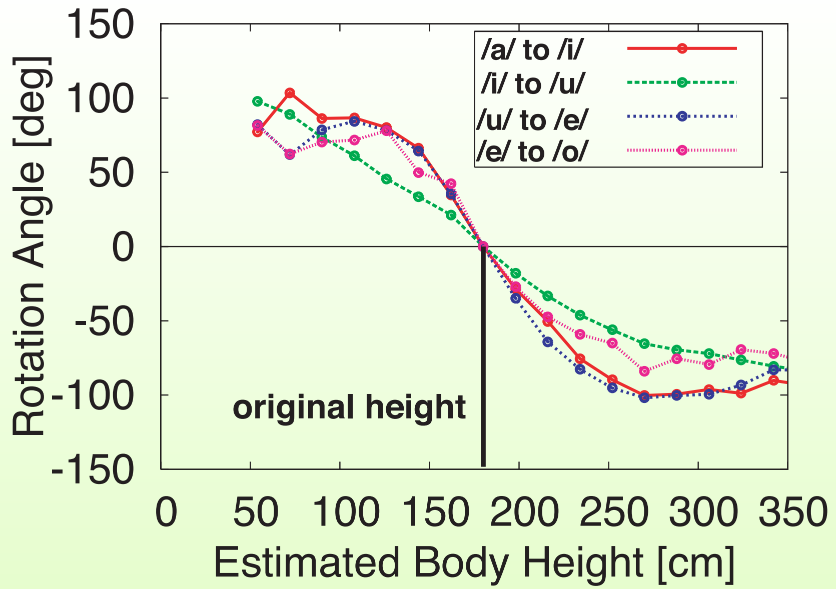
$$\boldsymbol{R}^t\boldsymbol{R} = \boldsymbol{R}\boldsymbol{R}^t = \boldsymbol{I}$$

$$\det \boldsymbol{R} = +1.$$

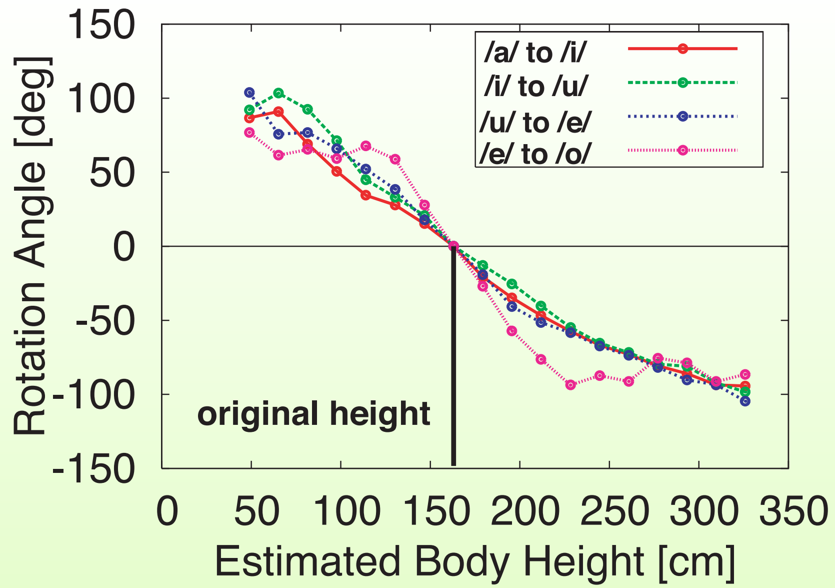
$$a_{ij} = \frac{1}{(j-1)!}\sum_{m=\max(0,j-i)}^{j}\binom{j}{m}\times\frac{(m+i-1)!}{(m+i-j)!}(-1)^m\alpha^{(2m+i-j)}$$

satisfied this condition approximately.

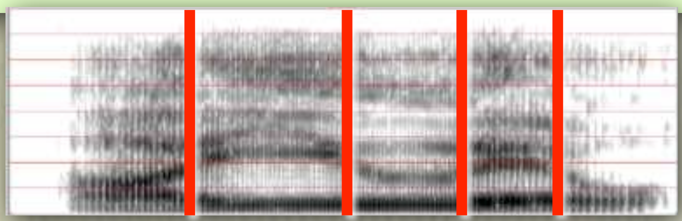
Frequency warping can rotate any cepstrum trajectory.



(a):MFCC (male)

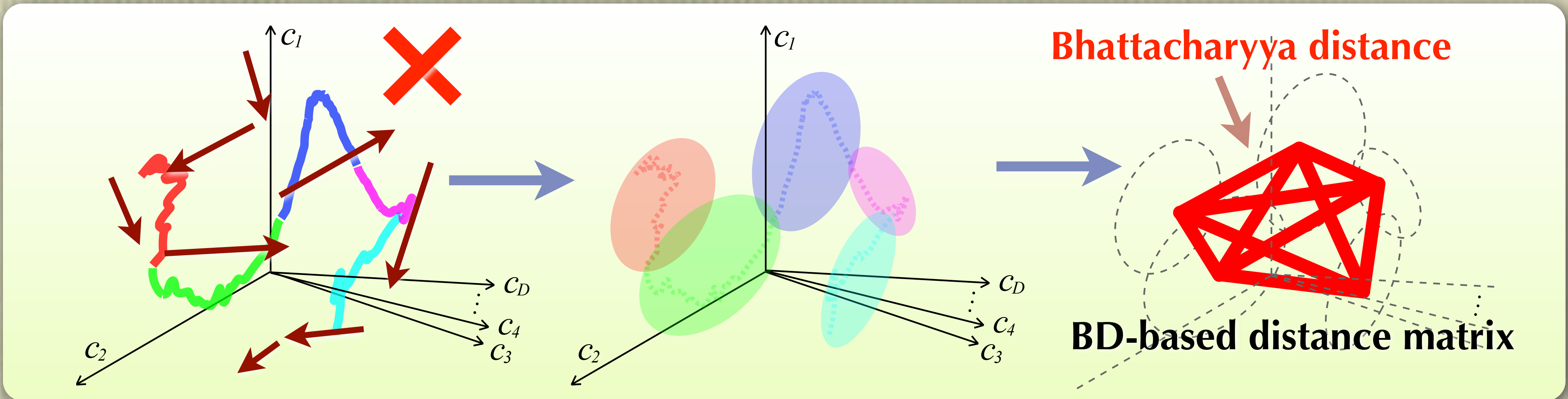


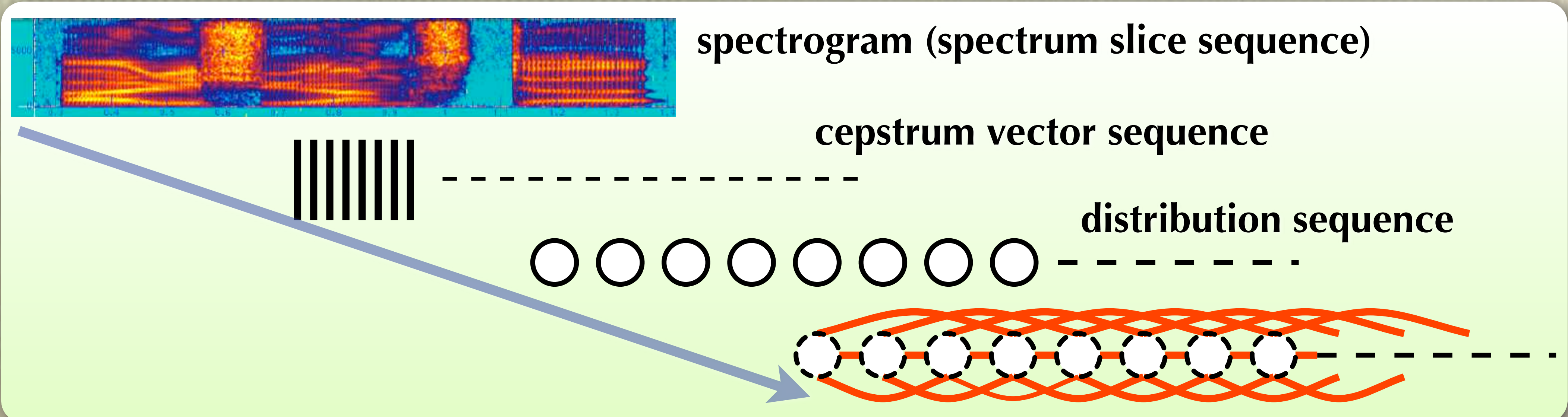
(d):MFCC (female)



Invariant speech structure

Utterance to structure conversion using *f*-div. [Minematsu'06]





- An event (distribution) may be smaller than a phoneme.

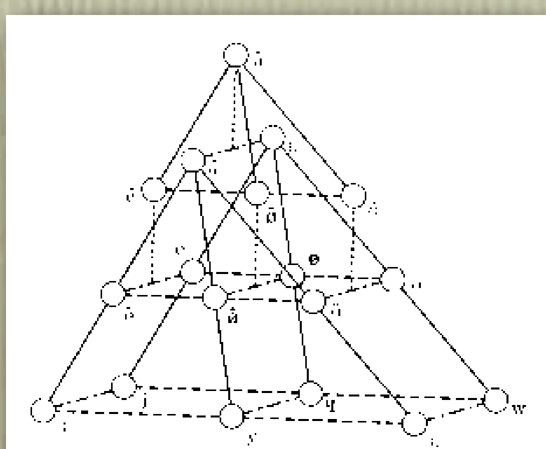
A claim found in classical linguistics

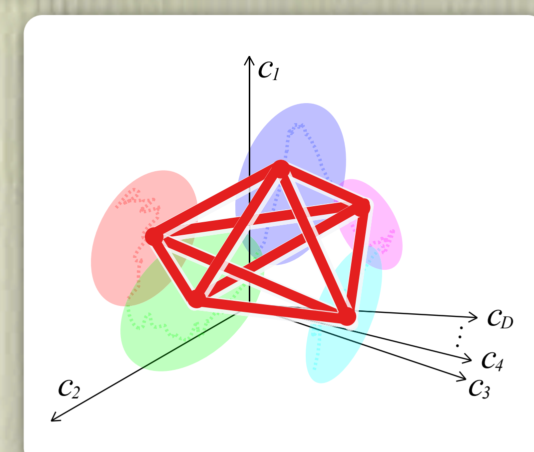
Theory of relational invariance [Jakobson+'79]

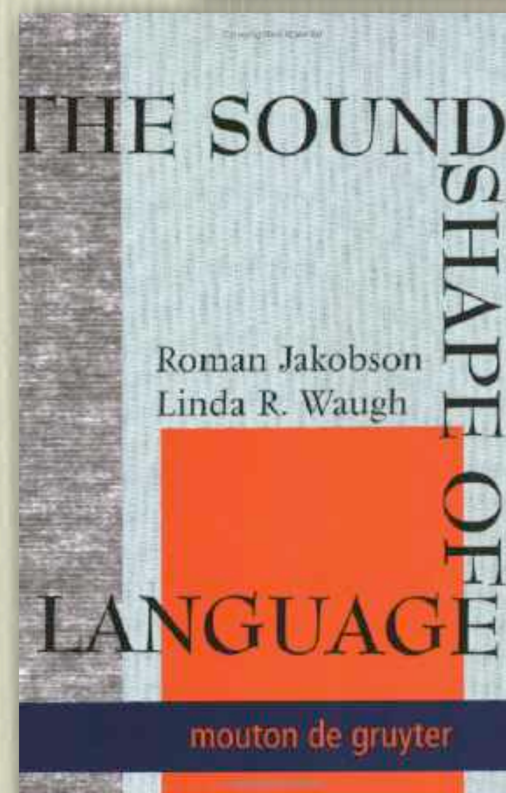
- Also known as theory of distinctive features
- Proposed by R. Jakobson

> We have to put aside the accidental properties of individual sounds and substitute a general expression that is the common denominator of these variables.

> Physiologically identical sounds may possess different values in conformity with the whole sound system, i.e. in their relations to the other sounds.



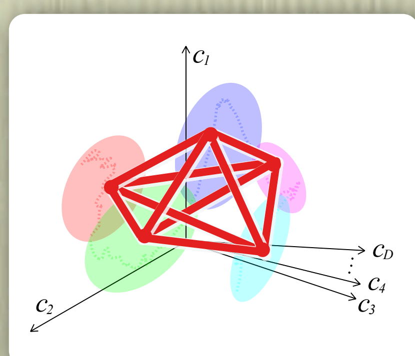


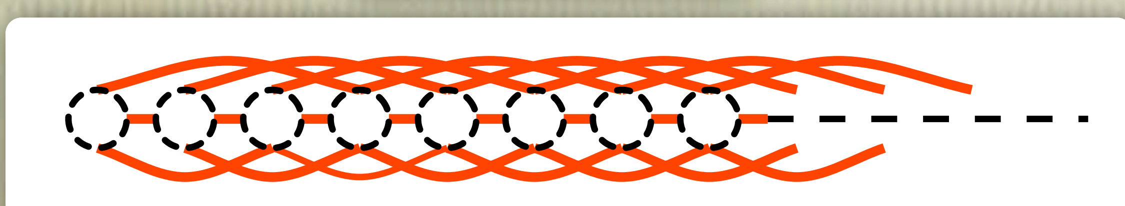


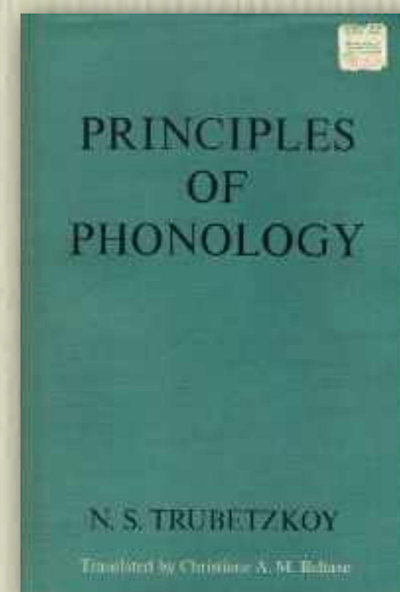
More classical claims in linguistics

Nikolay Sergeevich Trubetskoy (1890-1938)

- "The Principles of Phonology" (1939)
- The phonemes should not be considered as building blocks out of which individual words are assembled. Each word is a phonic entity, a Gestalt, and is also recognized as such by the hearer.
- As a Gestalt, each word contains something more than sum of its constituents (phonemes), namely, the principle of unity holds the phoneme sequence together and lends individuality to a word.



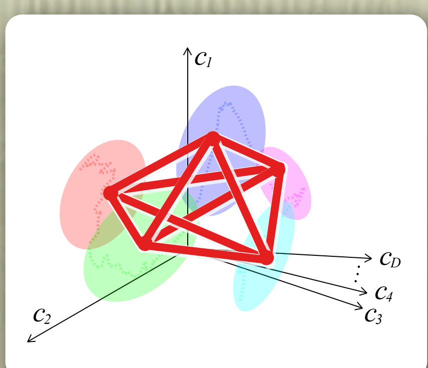




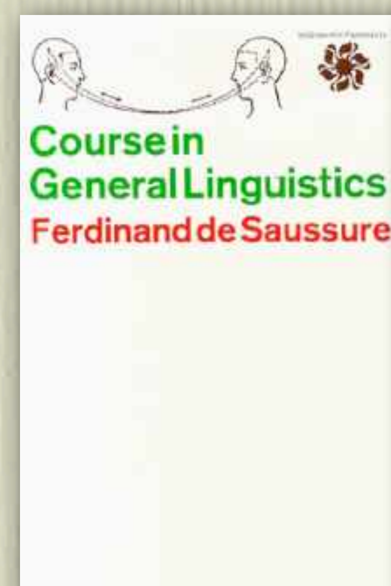
More classical claims in linguistics

Ferdinand de Saussure (1857-1913)

- Father of modern linguistics
- "Course in General Linguistics" (1916)
- What defines a linguistic element, conceptual or phonic, is the relation in which it stands to the other elements in the linguistic system.
- The important thing in the word is not the sound alone but the phonic differences that make it possible to distinguish this word from the others.
- Language is a system of only conceptual differences and phonic differences.



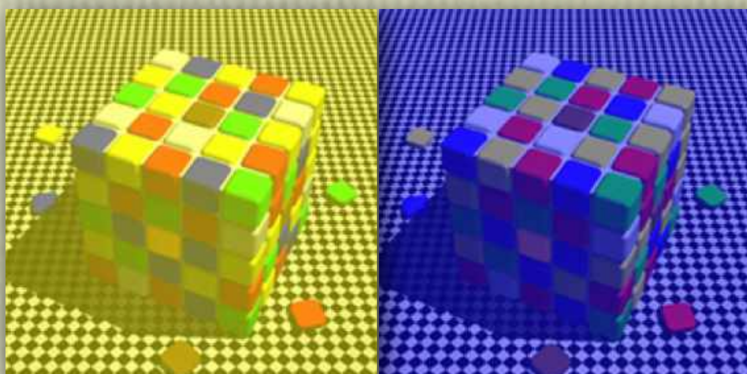
$$\begin{bmatrix} d_{11} & d_{12} & \dots & d_{1N} \\ d_{21} & d_{22} & \dots & d_{2N} \\ d_{31} & & & \\ \vdots & & & \\ d_{N1} & d_{N2} & \dots & d_{NN} \end{bmatrix}$$



Invariant timbre perception against its bias

Invariant and constant perception wrt. color and pitch

- Contrast-based information processing is important.
- Holistic & relational processing enables element identification.



Invariant and constant perception wrt. timbre

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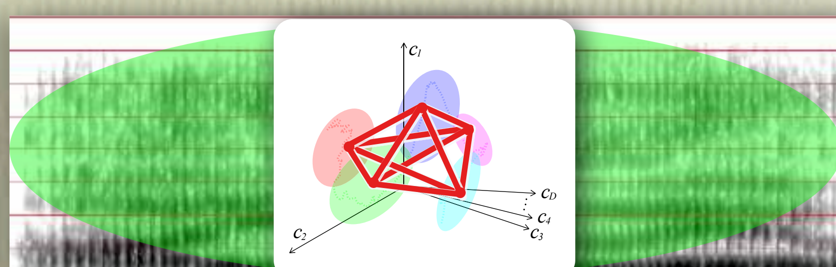
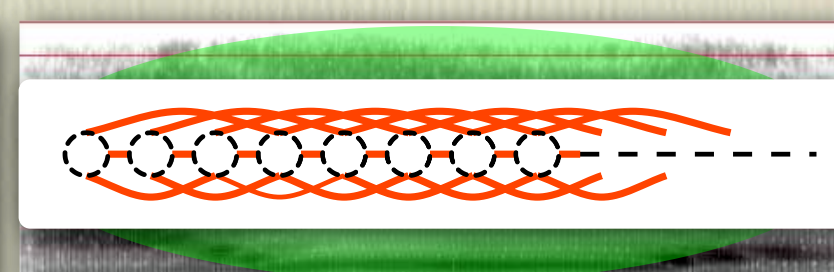
- Holistic & relational processing enables element identification.



Menu of the last four lectures

- **Robust processing of easily changeable stimuli**
  - Robust processing of general sensory stimuli
  - Any difference in the processing between humans and animals?
- **Human development of spoken language**
  - Infants' vocal imitation of their parents' utterances
  - What acoustic aspect of the parents' voices do they imitate?
- **Speaker-invariant holistic pattern in an utterance**
  - Completely transform-invariant features -- *f*-divergence --
  - Implementation of word Gestalt as relative timbre perception
  - Application of speech structure to robust speech processing
- **Radical but interesting discussion**
  - An interesting link to some behaviors found in language disorder
  - An interesting thought experiment

!! Note !!

- **The next class on Dec 17 is cancelled.**
  - Minematsu will attend a workshop in Okinawa.
- **The last two classes are given on**
  - Dec 25 (Wed), starting at 14:55
    - Dec 24 (Tue) is a day for Friday classes.
  - Jan 7 (Tue), starting at 14:55.