A source/filter model with adaptive constraints for NMF-based speech separation

Damien Bouvier[1], Nicolas Obin[1], Axel Roebel[1], Marco Liuni[1]

[1]IRCAM, UPMC - Sorbonne Universités, CNRS

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State of the art

- Speech separation using NMF
- Semi-supervised NMF
- Source/filter model

Proposed method

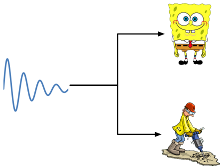
- Semi-supervised constrained NMF
- Contribution 1: speech-specific source/filter coherence constraint
- Contribution 2: adaptive weight method

Experimental evaluation

- Experiment description
- Effect of weight's adaptation
- Algorithm comparison

Speech separation using NMF

Signal has only 2 sources:
speech and background sound



Supervised algorithms

- [Mysore and Smaragdis, 2012]: language model
- [Virtanen et al., 2013]: new updates using Newton algorithm
- [Sun and Mysore, 2013]: Universal Speech Model (USM)

Semi-supervised algorithms

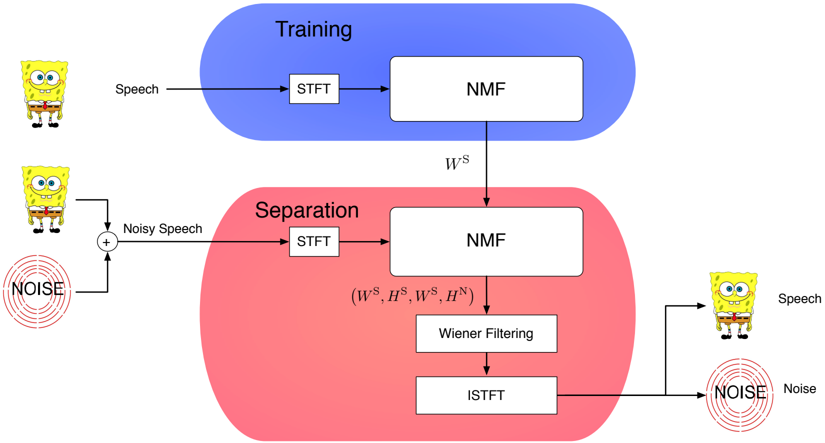
- [Germain and Mysore, 2015]: USM & online noise adaptation

Unspervised algorithms (but informed)

- [Le Magoarou et al., 2014]: use of textual information
- [Durrieu et al., 2009]: source/filter model for NMF

Semi-supervised NMF

$$\underset{\boldsymbol{W}^S,\boldsymbol{W}^N,\boldsymbol{H}^N \geq 0}{\operatorname{argmin}} \quad \mathcal{C}(\boldsymbol{V}|\widetilde{\boldsymbol{V}}) \text{ with } \begin{cases} \widetilde{\boldsymbol{V}} = \boldsymbol{W}^S\boldsymbol{H}^S + \boldsymbol{W}^N\boldsymbol{H}^N \\ \boldsymbol{W}^S \text{ learned} \end{cases} \tag{1}$$



Source/filter model [Durrieu et al., 2009]

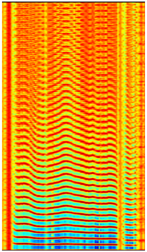
$$\text{source} \quad * \quad \text{filter} \quad = \quad \text{sound}$$

$$\text{glottis} \longrightarrow \boxed{\text{vocal tract}} \longrightarrow \text{speech}$$

Source/filter model [Durrieu et al., 2009]

source $*$ filter $=$ sound

glottis $\longrightarrow$ $\boxed{\text{vocal tract}}$ $\longrightarrow$ speech



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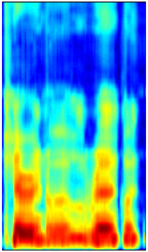

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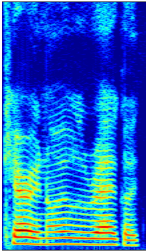

$$\boldsymbol{V}^{\text{ex}} \;.*\; \boldsymbol{V}^{\Phi} = \boldsymbol{V}$$

Source/filter model [Durrieu et al., 2009]

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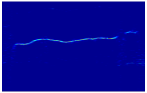
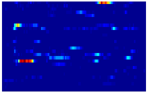
glottis ⟶ $\boxed{\text{vocal tract}}$ ⟶ speech

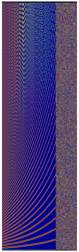
$\boldsymbol{H}^{\text{ex}}$

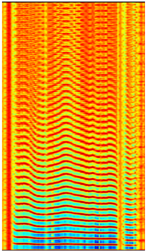


$\boldsymbol{H}^{\Phi}$



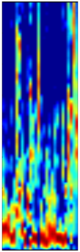
$\boldsymbol{W}^{\text{ex}}$

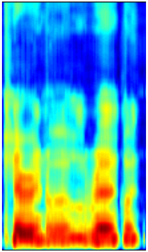




.*

$\widehat{\boldsymbol{W}}^{\Phi}$





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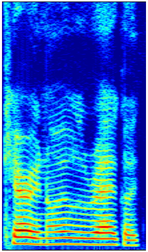
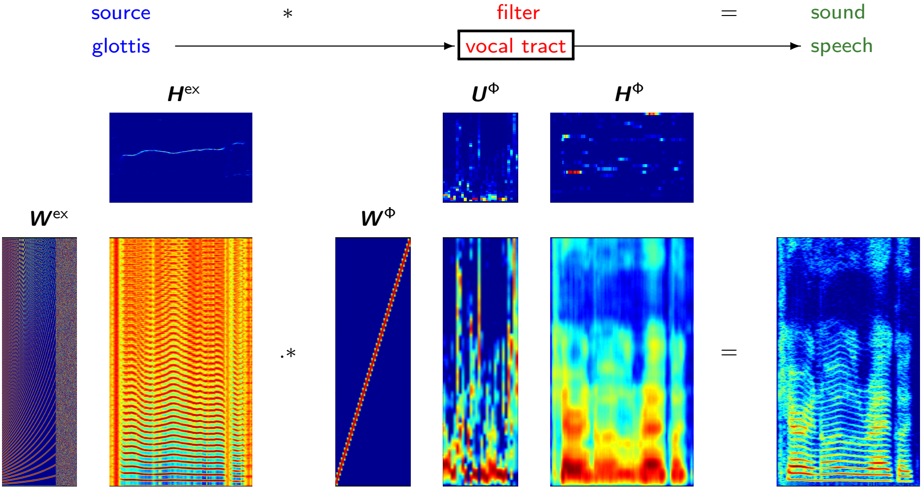


$$\left(\boldsymbol{W}^{\text{ex}} \quad \boldsymbol{H}^{\text{ex}}\right) \quad .* \quad \left(\widehat{\boldsymbol{W}}^{\Phi} \quad \boldsymbol{H}^{\Phi}\right) \quad = \quad \boldsymbol{V}$$

Source/filter model [Durrieu et al., 2009]



$$(\boldsymbol{W}^{\mathrm{ex}} \quad \boldsymbol{H}^{\mathrm{ex}}) \quad .* \quad \left(\boldsymbol{W}^{\Phi} \quad \boldsymbol{U}^{\Phi} \quad \boldsymbol{H}^{\Phi}\right) \quad = \quad \boldsymbol{V}$$

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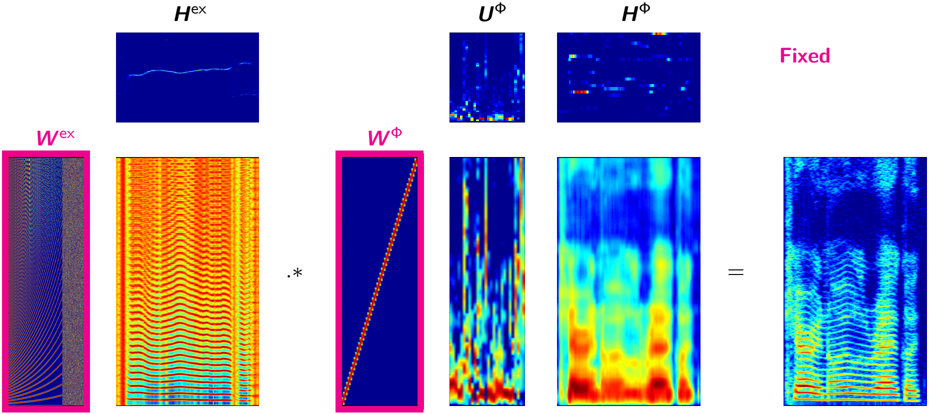

$$(\boldsymbol{W}^{\mathrm{ex}} \boldsymbol{H}^{\mathrm{ex}}) .* (\boldsymbol{W}^{\Phi} \boldsymbol{U}^{\Phi} \boldsymbol{H}^{\Phi}) = \boldsymbol{V}$$

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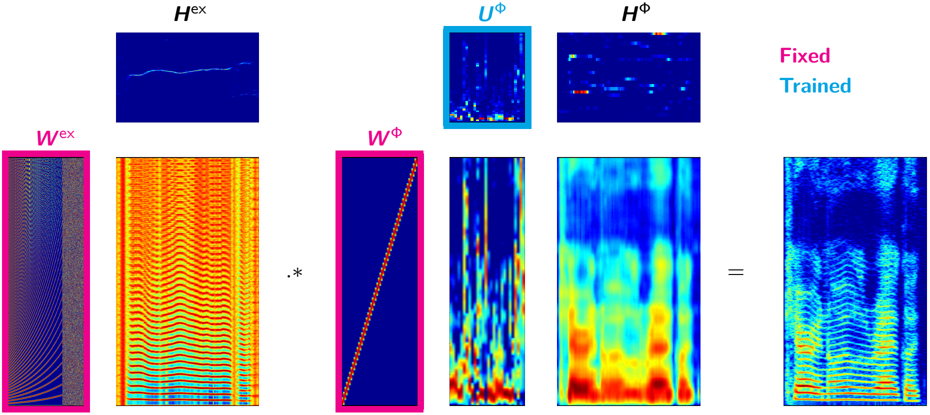

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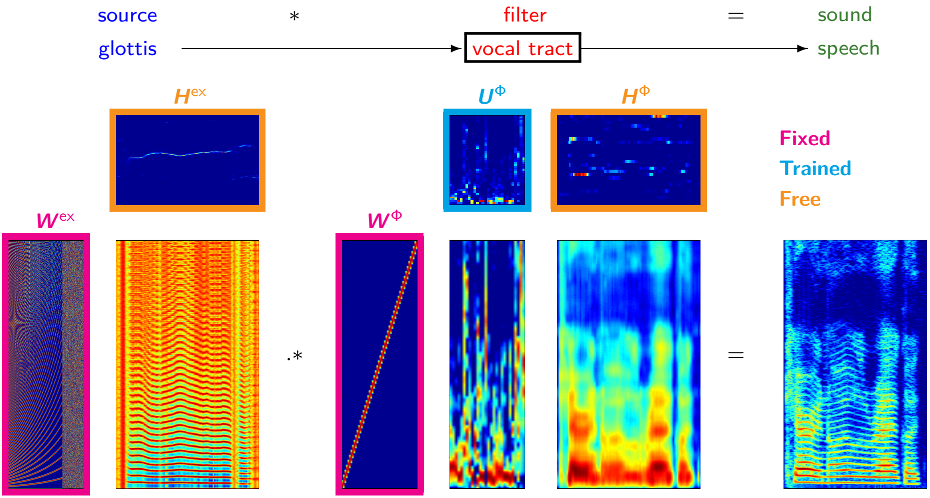

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Semi-supervised constrained NMF

Physically-informed model

$$\underset{\boldsymbol{H}^{\text{ex}},\boldsymbol{H}^{\Phi},\boldsymbol{W}^{N},\boldsymbol{H}^{N}\geq 0}{\operatorname{argmin}} \mathcal{C}(\boldsymbol{V}|\widetilde{\boldsymbol{V}}) \text{ with } \begin{cases} \widetilde{\boldsymbol{V}} = \boldsymbol{W}^{\text{ex}}\boldsymbol{H}^{\text{ex}} \otimes \boldsymbol{W}^{\Phi}\boldsymbol{U}^{\Phi}\boldsymbol{H}^{\Phi} + \boldsymbol{W}^{N}\boldsymbol{H}^{N} \\ \boldsymbol{W}^{\text{ex}} \text{ and } \boldsymbol{W}^{\Phi} \text{ fixed} \\ \boldsymbol{U}^{\Phi} \text{ learned} \end{cases} \quad (2)$$

But still no physically-coherent behavior.

Semi-supervised constrained NMF

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But still no physically-coherent behavior.

Constraints for controlling its behavior

$$\underbrace{\mathcal{C}(\boldsymbol{V}|\widetilde{\boldsymbol{V}})}_{\text{Total cost}} = \underbrace{D(\boldsymbol{V}|\widetilde{\boldsymbol{V}})}_{\text{Reconstruction cost}} + \overbrace{\lambda}^{\text{Weight parameter}} \underbrace{\mathcal{P}(\boldsymbol{\Theta})}_{\text{Constraint penalty}} \tag{3}$$

Semi-supervised constrained NMF

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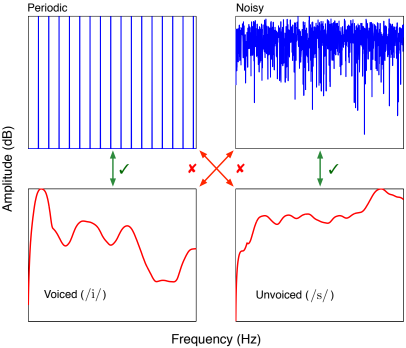
New multiplicative update rules :

$$\boldsymbol{\Theta}^{(i+1)} \longleftarrow \boldsymbol{\Theta}^{(i)} \otimes \frac{\nabla^{-}_{\boldsymbol{\Theta}} D + \lambda \nabla^{-}_{\boldsymbol{\Theta}} \mathcal{P}}{\nabla^{+}_{\boldsymbol{\Theta}} D + \lambda \nabla^{+}_{\boldsymbol{\Theta}} \mathcal{P}} \quad \forall \boldsymbol{\Theta} \in \left\{ \boldsymbol{H}^{\text{ex}}, \boldsymbol{H}^{\Phi}, \boldsymbol{W}^{N}, \boldsymbol{H}^{N} \right\} \tag{4}$$

Constraints from literature [Bertin, 2009]: Sparsity, Decorrelation, Smoothness.

Contribution 1: speech-specific source/filter coherence constraint

Problem: unrealistic source/filter combinations possible



We only want to allow:

- periodic excitation with adequate filter (e.g. vowels, voice consonants)
- noisy excitation with adequate filter (e.g., unvoiced consonants)

Contribution 1: speech-specific source/filter coherence constraint

New constraint (that requires phoneme-labelled spectral filter basis)

$$\mathcal{P}_{\phi}(\boldsymbol{H}^{\text{ex}}, \boldsymbol{H}^{\Phi}) \tag{5}$$

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$$\mathcal{P}_\phi(\boldsymbol{H}^{\mathrm{ex}}, \boldsymbol{H}^{\Phi}) = \sum_{\substack{k \in \mathrm{periodics} \\ l \in \mathrm{unvoiced}}} \frac{\left[\boldsymbol{H}^{\mathrm{ex}} \boldsymbol{H}^{\Phi\,T}\right]_{kl}}{} \quad (5)$$

- : measure of correlation

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- : measure of correlation
- : normalized

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- : measure of correlation
- : normalized
- : for both type of unwanted combination

Contribution 2: adaptive weight method

Main issue with constrained NMF

Adjusting the weight parameter λ :

- if too small, no effect is visible;
- if too big, convergence becomes extremely sensitive to initialization (which is typically random).

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Idea

Adjust the constraint weight at each iteration of the NMF:

- constraint relaxed during strong evolution of the reconstruction cost;
- constraint enforced when the reconstruction is more stable;

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Adaptive method

$$\lambda^{(i)} = \lambda_{Max} \frac{D(\boldsymbol{V}|\widetilde{\boldsymbol{V}}^{(i-1)})}{D(\boldsymbol{V}|\widetilde{\boldsymbol{V}}^{(i-2)})} \tag{6}$$

$$\left(\begin{array}{c} D(\boldsymbol{V}|\widetilde{\boldsymbol{V}}) \text{ the reconstruction cost} \\ \lambda \in [0 \ \lambda_{Max}] \end{array} \right)$$

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Experiment description

Database

TIMIT [Zue et al., 1990] : 20 speakers, 2 learnings sentences and 8 test sentences
QUT-NOISE [Dean et al., 2010] : 5 types of noise
Mixed at 3 Signal-to-Noise Ratio ($-6\mathrm{dB}$, $+0\mathrm{dB}$ and $+6\mathrm{dB}$)

Benchmark

SoA	• ASNA [Virtanen et al., 2013]	supervised
	• IMM [Durrieu et al., 2009]	unsupervised
Proposed	• S-IMM: without contrainsts	semi-supervised
	• SC-IMM1: state-of-the art contrainsts	
	• SC-IMM2: source/filter coherence constraint	
	• SC-IMM3: all constraints	

Measures

- SDR : Signal to Distortion Ratio (in dB)
- PESQ : Perceptual Evaluation of Speech Quality (from 1 (bad) to 5 (excellent))

Effect of weight's adaptation

SNR	Measure	With adaptation			Without adaptation		
		SC-IMM1	SC-IMM2	SC-IMM3	SC-IMM1	SC-IMM2	SC-IMM3
-6dB	SDR (dB)	4.1	**5.2**	**5.4**	4.1	5.0	5.2
	PESQ	1.91	**2.01**	**2.01**	1.91	1.94	1.92
$+0$dB	SDR (dB)	9.2	**9.8**	**9.8**	9.2	9.0	8.9
	PESQ	2.30	**2.34**	**2.35**	2.30	2.24	2.23
$+6$dB	SDR (dB)	**13.0**	**12.8**	**12.9**	12.8	11.1	10.9
	PESQ	**2.62**	**2.59**	**2.62**	2.61	2.46	2.44
Mean	SDR (dB)	8.7	**9.3**	**9.4**	8.7	8.4	8.3
	PESQ	**2.28**	**2.31**	**2.33**	2.27	2.21	2.20

$\Rightarrow$ **adaptation gives best results**

Algorithm comparison

SNR	Measure	Algorithms					
		ASNA	IMM	S-IMM	SC-IMM1	SC-IMM2	SC-IMM3
$-6\mathrm{dB}$	SDR (dB)	5.8	4.4	4.0	4.1	5.2	5.4
	PESQ	2.00	1.22	1.91	1.91	2.01	2.01
$+0\mathrm{dB}$	SDR (dB)	10.7	7.8	9.1	9.2	9.8	9.8
	PESQ	2.44	1.54	2.30	2.30	2.34	2.35
$+6\mathrm{dB}$	SDR (dB)	15.0	9.7	13.0	13.0	12.8	12.9
	PESQ	2.85	1.82	2.62	2.62	2.59	2.62
Mean	SDR (dB)	10.5	7.3	8.7	8.7	9.3	9.4
	PESQ	2.43	1.52	2.28	2.28	2.31	2.33

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$\Rightarrow$ **supervisation helps separation**

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$\Rightarrow$ **best proposed algorithm: SC-IMM3 (with all constraints)**

Algorithm comparison

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$\Rightarrow$ **better than Durrieu & close of Virtanen in low SNRs**

Speech

Noise

Text : *"Computers are being used to keep branch inventories at more workable levels."*

Conclusion

Summary

- Semi-supervised speech separation
- Source/filter model

Contributions

- Weight adaptation method for constraints
- Source/filter coherence constraint for speech
- Good results close to literature in supervised separation

Further research

- Speaker-independant model [Sun and Mysore, 2013]
- Integration of a language model [Mysore and Smaragdis, 2012]
- Integration of a noise adaptation method [Roebel et al., 2015]

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