A APPENDIX: HYPER-PARAMETER SELECTION FOR NON-NEGATIVE MATRIX FACTORIZATION

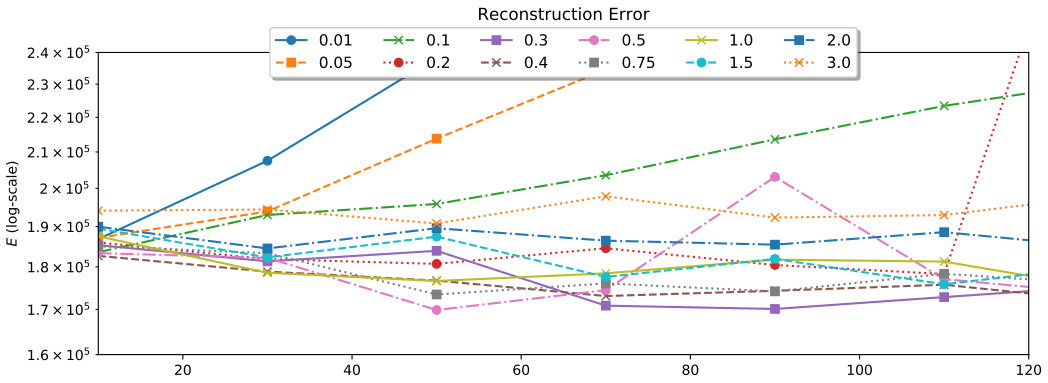

Figure 4: A zoom-in plot for the reconstruction errors.

Denote $M_t, M_v \in \{0,1\}^{n\times m}$ to be the mask matrices for indicating held-in and held-out entries of the input PPMI matrix P in CV procedure, we then optimize for O^* and V^*:

$$O^*, V^* = \underset{O,V}{\operatorname{argmin}} \|M_t \odot (P - OV^T)\|_F^2 + \beta\mathcal{R}(O,V). \tag{6}$$

To apply the multiplicative update scheme as proposed in (Lee & Seung, 2001), we first consider the partial derivatives with respect to O and V. Denote $F(O,V) \equiv \|M_t \odot (P - OV^T)\|_F^2 + \beta\mathcal{R}(O,V)$, we have

$$\begin{aligned} \nabla_O F(O,V) &= (M_t \odot OV^T)V - (M \odot P)V + \beta \cdot \mathbf{1} \\ \nabla_V F(O,V) &= (M_t \odot OV^T)^T U - (M \odot P)^T U + \beta \cdot \mathbf{1}. \end{aligned} \tag{7}$$

We then have the following update rules that is guaranteed to be non-increasing:

$$\begin{aligned} O^{(i+1)} &\leftarrow O^{(i)} \odot \frac{(M_t \odot P)V^{(i)}}{(M_t \odot O^{(i)}(V^{(i)})^T)V^{(i)} + \beta} \\ V^{(i+1)} &\leftarrow V^{(i)} \odot \frac{(M_t \odot P)^T U^{(i)}}{(M_t \odot O^{(i)}(V^{(i)})^T)^T U^{(i)} + \beta}, \end{aligned} \tag{8}$$

where the fraction here represents elementary-wise division. For the choice of M_t and M_v, we follow the same approach as proposed in (Kanagal & Sindhwani, 2010). We first split the matrix into K blocks, where the rows and columns are randomly shuffled. Denote $\mathtt{r}^{(k)}$ and $\mathtt{c}^{(k)}$ to be the index vectors for rows and columns respectively, where $\mathtt{r}_i^{(k)} = 1$ if row i contains in block k, or $\mathtt{c}_j^{(k)} = 1$ if column j contains in block k. The mask for k-th block can then be expressed as $M^{(k)} = \mathtt{r}^{(k)} \otimes \mathtt{c}^{(k)}$. We then randomly select q out of K blocks as holdout blocks, which gives

$$M_v = \sum_{s=1}^{q} \mathtt{r}^{(k_s)} \otimes \mathtt{c}^{(k_s)}, \quad M_t = \mathbf{1} - M_v, \tag{9}$$

where k_s is the index of selected block. The reconstruction error E can thus be computed:

$$E = \|M_v \odot (P - O^*(V^*)^T)\|_F^2 + \beta\mathcal{R}(O^*, V^*). \tag{10}$$

Figure 4 shows a zoom-in plot of the reconstruction error under different combinations of d and β. For every (d, β) setting, we perform multiple optimization since NMF is sensitive to initialization. We then choose $d = 70$ and $\beta = 0.3$ accordingly. Empirically, we observe that the rank selection is quite robust to over-fitting when there is a sufficient sparsity control, for instance, $\beta > 0.1$ in our dataset. We also observe that whenever $d \in [50, 150]$ and $\beta \in [0.05, 0.5]$, the results are similar.

B APPENDIX: DISTRIBUTION OF AAUCS ON WTACTION AND MSCOCO DATASET

The following figures show the AAUC distribution of the top 5 embeddings on the WTaction and MSCOCO dataset respectively.

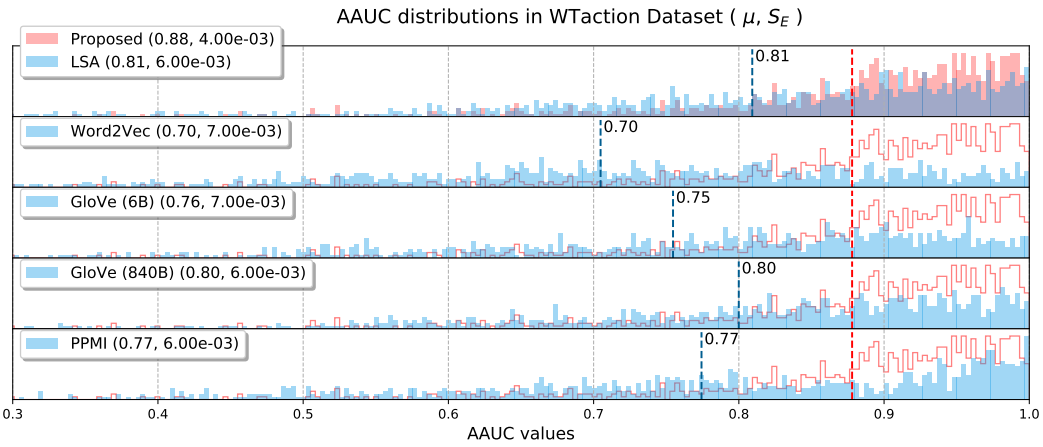

Figure 5: AAUC Distribution on WTaction Dataset

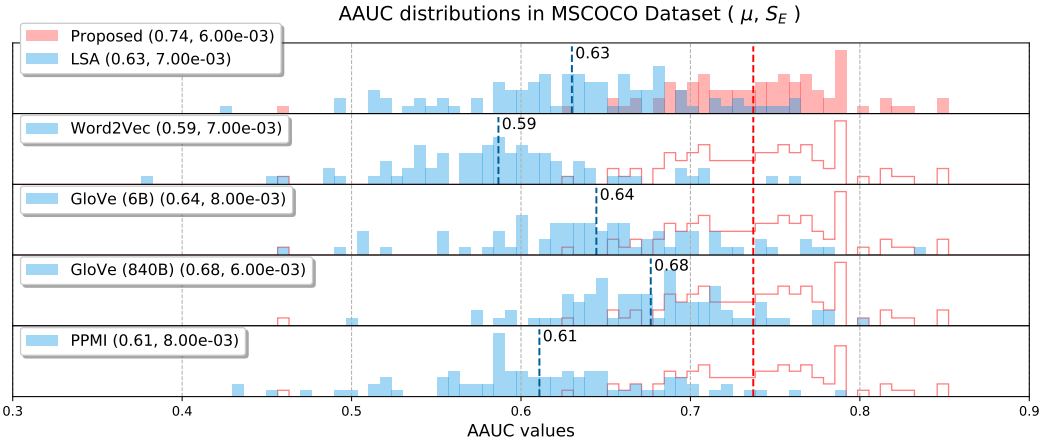

Figure 6: AAUC Distribution on MSCOCO Dataset

C APPENDIX: AFFORDANCES ASSIGNMENT FOR EACH SPOSE DIMENSION

Pearson correlation	Dimension label	Taxonomy	Affordances (Top Ten Ranked Verbs)
0.84	animal	categorical	kill, spot, hunt, observe, chase, feed, slaughter, sight, trap, find
0.82	food	categorical	serve, eat, cook, prepare, taste, consume, add, mix, stir, order
0.75	wearable	categorical	wear, don, match, knit, sew, fasten, rip, embroider, tear, model
0.75	vehicle	categorical	drive, hire, park, equip, rent, commandeer, crash, board, build, operate
0.71	plant	categorical	grow, cultivate, plant, add, eat, chop, gather, cut, dry, prune
0.68	musical instrument	categorical	hear, sound, play, learn, amplify, blare, study, tootle, toot, tinkle
0.68	electronic device	categorical	install, operate, connect, activate, invent, disconnect, manufacture, purchase, incorporate, design
0.67	made of metal	structural	fit, invent, manufacture, incorporate, design, position, attach, utilize, carry, install
0.66	body/clothing	categorical	wear, don, straighten, slash, bandage, hurt, rip, injure, heal, model
0.63	bug	categorical	kill, catch, spot, observe, find, eradicate, deter, trap, hunt, feed
0.63	drink	categorical	drink, pour, quaff, sip, guzzle, sup, swig, spill, imbibe, gulp
0.61	tool	categorical	wield, grab, hold, carry, sharpen, swing, hand, pick, clutch, throw
0.57	can tie	functional	fasten, tighten, unfasten, undo, attach, thread, tie, secure, loosen, loose
0.55	marine	categorical	spot, beach, moor, sail, observe, find, sight, capsize, catch, call
0.54	granulated	structural	contain, mix, scatter, add, gather, remove, sprinkle, dry, deposit, shovel
0.52	valuable/old	functional	steal, discover, find, carve, place, design, contain, recover, craft, hide
0.52	object (house)	categorical	design, manufacture, fit, incorporate, install, place, fill, purchase, clean, buy
0.52	aeronautic	categorical	spot, observe, sight, destroy, build, construct, find, photograph, equip, design
0.52	outdoors	categorical	remove, construct, place, surround, incorporate, carry, erect, design, fit, build
0.50	body part	categorical	sprain, fracture, bandage, flex, injure, rest, bruise, straighten, hurt, hyperextend
0.50	weapon	categorical	throw, carry, hurl, drop, grab, wield, retrieve, fire, hold, toss
0.48	flammable	functional	light, extinguish, ignite, throw, carry, flash, kindle, place, manufacture, douse
0.47	textured	appearance	remove, place, hang, tear, stain, spread, weave, clean, drape, wrap
0.44	round	appearance	grow, cultivate, pick, add, slice, place, eat, chop, throw, plant
0.44	accessory (beauty)	categorical	steal, wear, find, place, gather, pick, remove, contain, give, sell
0.42	mineral/gem	categorical	steal, discover, recover, contain, retrieve, find, hide, place, remove, incorporate
0.42	accessory (face)	categorical	wear, remove, don, place, design, buy, call, pull, bring, find
0.40	made of wood	structural	place, remove, carry, incorporate, design, contain, bring, construct, manufacture, find
0.40	container	functional	empty, fill, carry, place, clean, load, bring, dump, unload, leave
0.38	elongated	structural	grab, carry, wield, hold, pick, place, throw, hand, bring, drop
0.38	structure	structural	incorporate, construct, fit, design, erect, position, install, mount, place, build
0.38	object (bath)	categorical	manufacture, remove, place, invent, clean, buy, put, apply, contain, design
0.37	string-like	appearance	remove, cut, place, pull, wrap, attach, manufacture, contain, call, bring
0.36	wheeled	functional	drive, manufacture, hire, design, equip, fit, rent, park, purchase, invent
0.36	made of paper	structural	manufacture, design, purchase, buy, place, invent, introduce, incorporate, fit, sell
0.33	appliance/machine	categorical	fit, manufacture, connect, design, install, incorporate, attach, utilize, purchase, invent
0.32	sport (ball)	categorical	manufacture, design, invent, buy, purchase, grab, carry, introduce, fit, bring
0.32	object (children)	categorical	buy, manufacture, design, purchase, bring, find, sell, introduce, steal, call
0.31	agglomerate	appearance	place, contain, add, remove, sell, manufacture, combine, find, buy, steal
0.29	flat surface	appearance	place, bring, remove, put, grab, hang, wrap, manufacture, buy, pull
0.28	circular	appearance	place, incorporate, fit, invent, remove, manufacture, design, call, position, utilize
0.26	accessory (black)	categorical	remove, grab, manufacture, buy, place, design, bring, wear, carry, invent
0.24	colorful pattern	appearance	manufacture, buy, design, place, remove, sell, invent, purchase, contain, bring
0.23	object (medical)	categorical	invent, place, remove, find, contain, manufacture, design, bring, carry, buy
0.23	craft	appearance	place, bring, remove, design, hang, call, buy, put, pull, manufacture
0.22	permeable	structural	fit, incorporate, remove, place, design, manufacture, install, position, clean, attach
0.18	object (small)	categorical	place, call, remove, buy, find, bring, manufacture, introduce, contain, incorporate
0.18	degree of red	appearance	place, call, add, contain, remove, find, buy, bring, introduce, sell
0.12	furry	appearance	place, call, find, remove, buy, bring, introduce, contain, add, manufacture

Table 3: Affordance assignment for SPoSE vectors ordered in terms of Pearson correlation with regression outcomes. The dimension labels are vastly simplified. The full descriptions for each dimension are provided in Appendix D (Table 4 and Table 5).

D APPENDIX: FULL DESCRIPTIONS FOR EACH SPOSE DIMENSION

The abbreviation and the full description of every SPoSE dimension.

Abbreviation	Full descriptions
accessory (black)	accessories, beauty, black, blackness, classy, date, emphasize, fancy, hair, hard, high-class, manly, objects, picture, telescope
accessory (face)	accessories, body parts, culture, decoration, eyes, face, face accessories, facial, goes on head, hair, head, less appealing, senses, touches face, wearable
accessory (beauty)	accessory, beautiful, beauty, color, fancyness, feminine, feminine items, floral, flowers, flowery, gentle, girly, love, muted colors, pastel, pink
aeronautic	aero-nautic, air, airplanes, aviary, aviation, buoyant, flies, flight, fly, flying, flying to not, high in air, light, move, sky, swim, transportation, travel
agglomerate	accumulatable, bundles, collection, colors, countable, grainy to smooth, group of similar things, groupings, groups, groups of small objects, large groups, little bits of things, many, metals, nuts, objects, patterns, piles, quantity of objects in photo, round, small, small objects in groups, small parts that look alike, symmetrical
animal	animal, animals, animals in zoo, animals that do not fly, from complex to less, fuzzy, grass, ground animals, land animals, mammal, mammals, natural, size, wild animals, wild to human-made, wilderness
appliance/machine	building materials, construction, destructive, electric items, factory, farm tools, foundation, home tools, in groups, long, machinery, maintenance, mostly orange, processing, renovation, rocks, rope-like, thing, tool, tools
body part	body, body parts, esp extremities, extremities, extremities of body, feet, feet to hands, fingers, found on people, hand, hands, human, legs, limbs, lower body, skin
body/clothing	bodies, body, body accessories, body maintenance, body part- related, body parts, body parts with hair, face, how much skin showing, human, human body parts, part of body, parts, people, skin, touched by skin
bug	animals that stick onto things, ants, bug, bugs, can hurt you, dangerous, gardening, insects, interact with bugs, small animals, small to large, wild
can tie	bands, bondages, can tie, chained, circles, coils, construction, fasteners, knotting, long, rope, ropes, round, string-like, strings, tensile, thing can tie around, tied, ties, trapped, violent, wires, wrap, wrapped around to what gets wrapped
circular	circles, circular, cylindrical, discs, flat, round, shape, targets
colorful pattern	artistic, bright, bright colors, color, color variety, color vibrancy, colorful, colors, many colors, patterns
container	able to put something in it, boxes, buckets, can put things into, carts, container, containers, containers for liquids, containing, covering, cylinders, diverse, drums, enclosed objects, hold other things, hollow tubes, paints, shapes, storage, unknown
craft	a lot of patterns, art, artisinal, arts, candles, circles, color, crafts, detailed dots, do-it-yourself, grandma, grandparent-like, handmade, home patterns, home-making related, housework, in grandma's home, intricacy, quilt, rectangles, sewing, specks, stitching, twine, unknown, weaving, wood, woven, yarn
degree of red	color, colors, degree of redness, red, red (bright)
drink	3-dimensional, beverage, containers, containers for liquids, drinks, edible, glass, glasses, hold liquid, liquid, liquids, other things, things that fit in containers, things that hold liquids, vessels with liquids, viscosity
electronic device	digital, digital devices, digital media, electric, electronic, electronics, hard, hard to understand, media, old technology, technological, technology, telephones, typing instruments
elongated	able to be held, cane, cylinders, cylindrical, darts, grouped, long, long narrow, long objects, long-shaped, narrow, pen-like, pencils, pens, shape, sharp, skinny rectangles, stick-like, sticks, straight, straight to curved, symmetrical, thin
flammable	fire, flammability, flammable, heat, hot, light, outdoors, warm
flat surface	attaching, breakable, clean, cloth, convenience, disposable, flat coverings, gathering, grated pattern, handle everyday, helpful, hold things in, multi-shaped, not smooth to smooth, paper, paper-like, sheets, stick-like, thin, things that roll, tissue, white
food	baked food, baked goods, carbs, cheesy, comforting, cooked, deliciousness, edible, entrees, food, made dish, natural products, nutrients, pastry, prepared food, processed, salt, where it comes from
furry	fluffy, furry, more of one color, white, white and fluffy, winter
granulated	a lot of items, ash, color, dirt, elements, grain-looking, grains, grainy, grainyness, granular objects, ground, ground (grinded), homogeneity, lots of same, many, not colorful, particles, rocky, shape, size of particles, small, small particles, stones, tiny groupings, tone, unknown minerals or drugs
made of metal	buckle, build, building, gray, hard, metal, metal tools, metallic, metallic tools, metals, shiny, silver, tools, use with hands
made of paper	books, card, classroom, collections, flatness, found in office, groups, has text, note-taking, office, paper, paper (colorful), papers, printed on, reading materials, rectangles, school, square, squares, stacks, striped, work
made of wood	brown, made of wood, natural, natural resources, orange, wood, wood-colored, yellow
marine	aquamarine life, aquatic activities, cruise, fish, in water, marine, nautical, ocean, outdoor, outside water, paradise, sea, ships, vacation, water

Table 4: Descriptions of abbreviation (A)

Abbreviation	Full descriptions
mineral/gem	beauty, clear minerals, crystal, earth-derived, gems, ice, in an artistic way, inspecting, intricate, jewelry, jewels, metallic, natural, natural minerals, prized, pure, rare, reflective, round, roundish, sharp, shiny, shinyness, sterile, translucent, valuable
musical instrument	control noise, hearing, instruments, listen, listening, loud, make noise, music, music instruments, musical, musical instruments, recreational instruments
object (bath)	bathroom, cleaning, essential everyday, gray, home (inside home), household items, hygiene, self-care, soap, toiletries, water, white
object (children)	baby, baby toys, child, child-like, children, dolls, toys, young, youth
object (house)	bland to colorful, chairs, cloth, common in household, everyday household, flat, furniture, house, house essentials, house surfaces, household commonness, household furniture, in house, living furniture, main component of room
object (medical)	health, health-concerning, hospital, hygiene, injury, medical, medical instruments, medical supplies, medicine, sick, to good health, unhealthy, water, wellness
object (small)	?, amish, appealing, candles, circular, color? Unsure, colorful, covers, cylinders, cylindrical, flat fat cylinders, hands-on, jewelry, lids, saving, shape, similar-shaped, things you grab, twine, unknown, yellow
outdoors	backyard, blue, brown colored, columns, common in outdoor, dirt, garden, landscape, man-made, monuments in nature, natural, nature, not colorful, outdoor objects, outdoorsy, park, pavement, pristine, public, quiet, rocks, rough, rows, scenery, separaters, stand on their own, statues, stone, tools, wood, woodsy, yard
permeable	can pass through, dot patterned, grates, holed, knit, little holes, mesh, metal, net, nets, octagonal, pattern, patterned, patterns, patterns (holes), repeated patterns, repeating, repeating patterns, repetitive, shiny, silver, small, strainer
plant	green, green leaves, green plants, green plants and herbs, greenery, greenness, greens, grow, natural, nature, plant-like, plants, things that grow from earth, vegetable, vegetables
round	artistic, ball, balls, circular, circular and colorful, circus, contrasting circles, fruits, kid, pictures, round, rund, shape, spherical
sport (ball)	athletic, ball toys, balls) to less active, competition, recreation, round, sport, sports, sports (active, sporty
string-like	amount of rigid ends, confetti, different shapes, elongated, hay, high-density, knots, lines, lines jutting out, long, long things mashed up, look like sticks, mesh, netting, patterns, prickly, protruding, repeating in an ordered way, rope, ropes, skinny, spiky, stacks, strings, stringy, symmetrical, tangled, twirled around
structure	amusement, antenna, big, caged, common to humans, complete, disordered, electrical, elongated, enclosures, found outside, grand, high, high in air, industrial, ladder, large, multiple cylinders, multiple similar things, narrow, outdoor, part of circle, shapes, stacks, structural, tall, things that go up, things that hang, trapped, wires
textured	appealing, carpets, flat coverings, fractals, lay flat, mesh, pattern, patterned, patterns, pieces, rectangles, repeating shapes, repetitive, rugs, sheets, small repeating patterns, squares, textured
tool	elongated, hand tools, household, jagged, long, pointy tools, pole, saws, scrape, sharp, sharp tools, small instruments, straight, tools, use with hands, utility, wedges
valuable/old	English royalty, antiquity, bottles, bronze, fine things, gaudiness, gold, high-class, high-quality, history, important, jewelry, jewels, monarchy, old, ornaments, precious metals, pristine, royal, royalty, shiny, silver, trophy, valueable
vehicle	can be moved, car, cars, complex vehicles, construction, efficiency of transportation, fast, ground motorized vehicles, machinery, mobility, move, speed of movement, transportation, transportation vehicles, travel with, truck, vehicles, wheeled vehicles, wheels
weapon	black, danger, dangerous, equipment, masculine, military, negatively-associated, ornaments, risky, self-defense, somber, violence, violent, war, war-like, weaponry, weapons
wearable	accessories, blue, can wear or carry or put on, clothes, clothing, cotton clothing, covering body, shirt, things to wear, things you wear, touch body, touch person, utilities, warm clothes, wearable
wheeled	able to hold, bicycle, caged, can sit on, can stand or drive, carrier, chair, destinations, holds objects, light movement, mobility, motion, move someone, playful, round, thing, things with wheels, trapped, wagon, wheel, wheeled-structures, wheels

Table 5: Descriptions of abbreviation (B)

E APPENDIX: COMPONENTS OF SPOSE DIMENSION APPROXIMATION

The following consecutive Figures 7–12 show the component information of each SPoSE dimension. The percentage is calculated based on the portion $w_i \cdot \|O_{:,i}\|$, where w_i is the regression coefficient corresponding to our i-th embedding dimension. The right ticks show the dimension affordances.

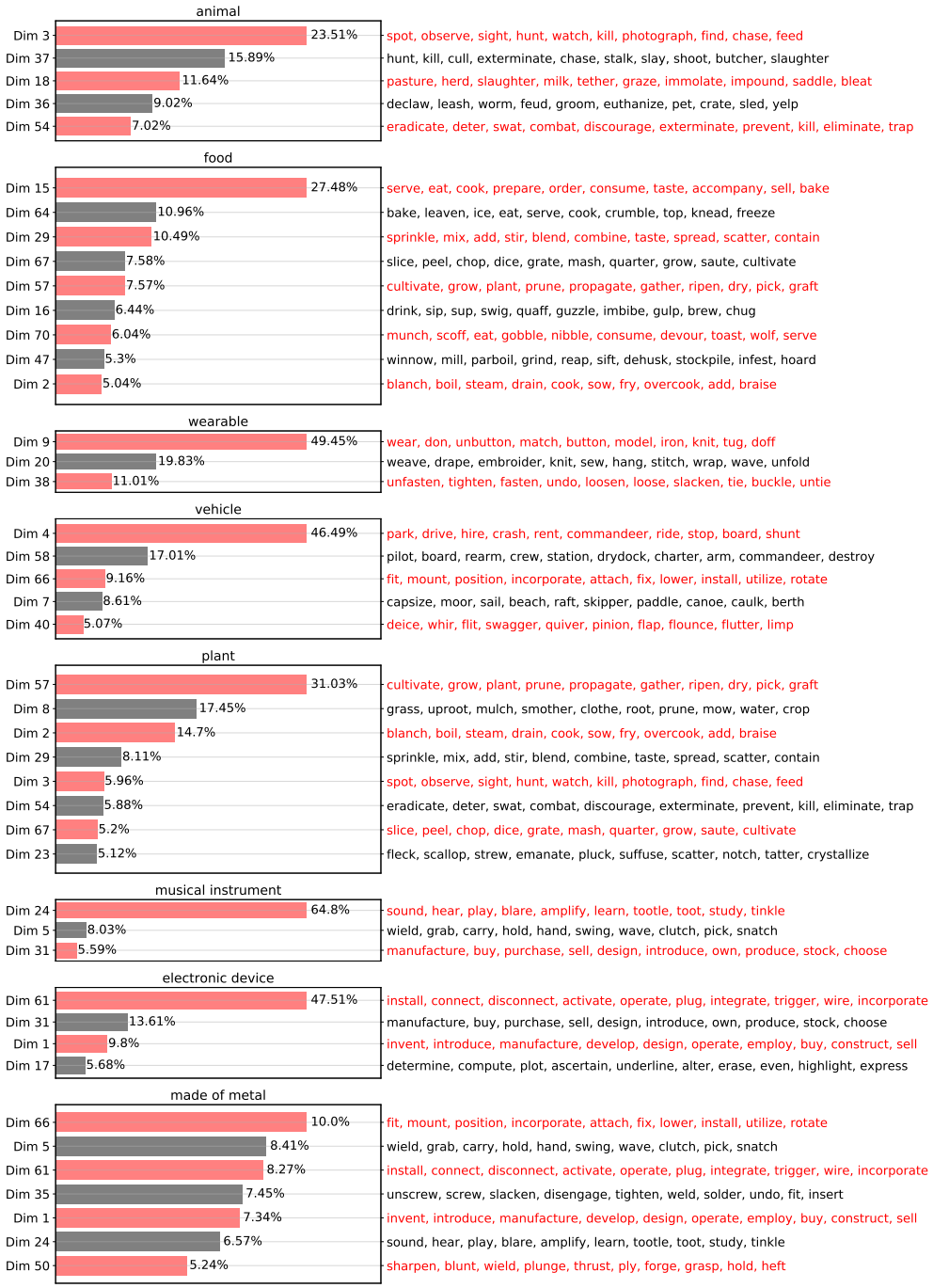

Figure 7: Components of SPoSE dimension approximation (A)

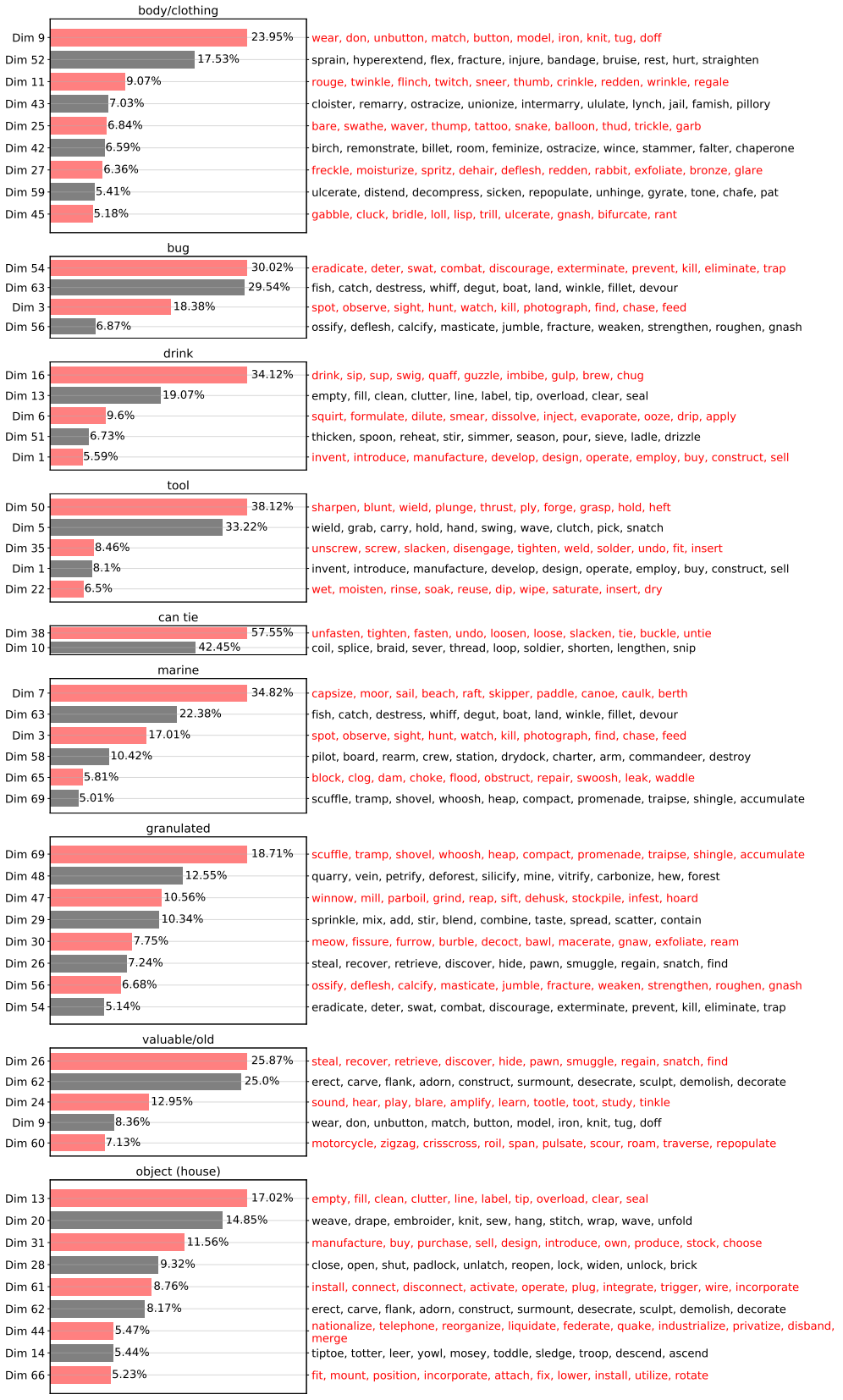

Figure 8: Components of SPoSE dimension approximation (B)

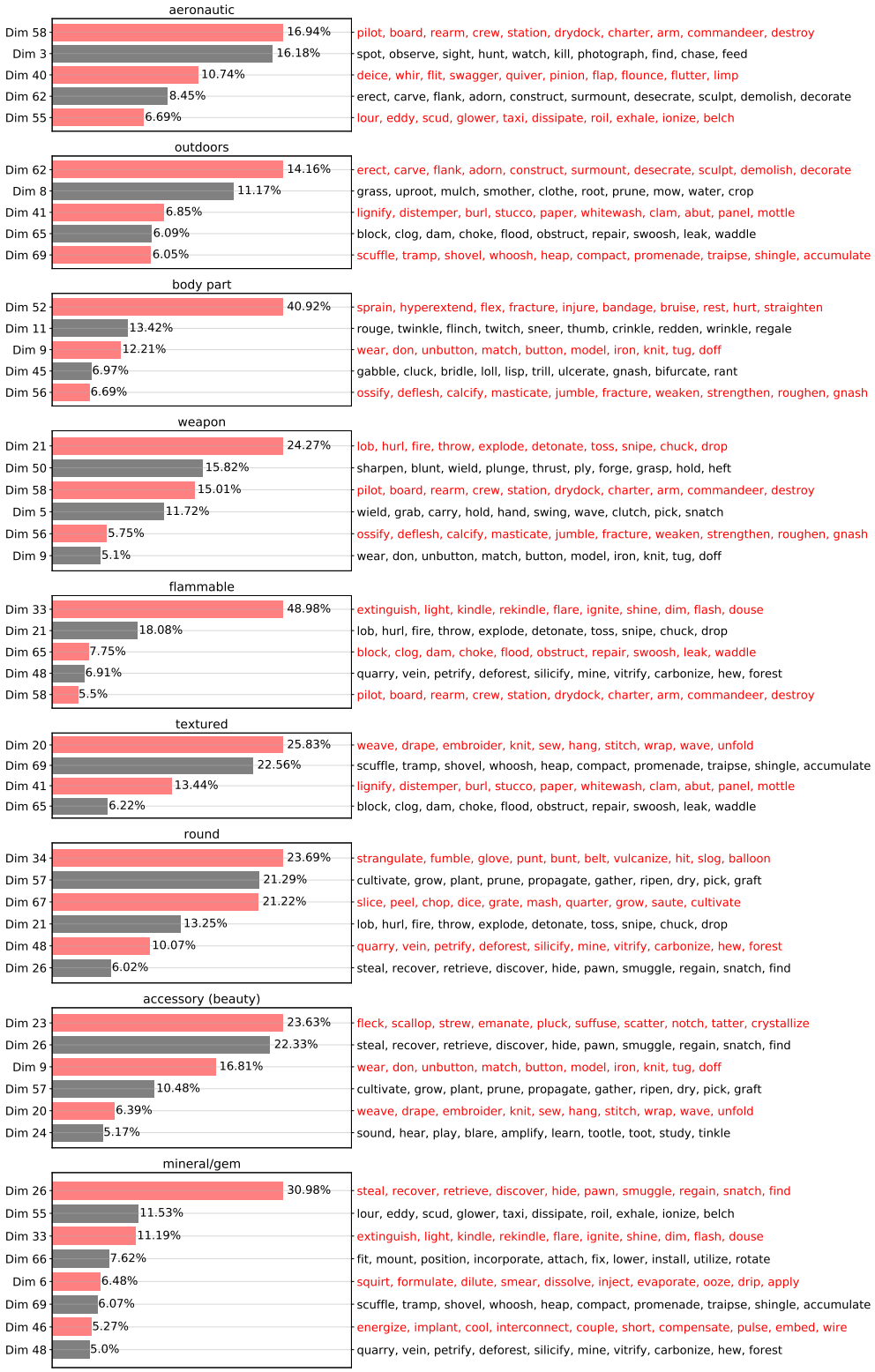

Figure 9: Components of SPoSE dimension approximation (C)

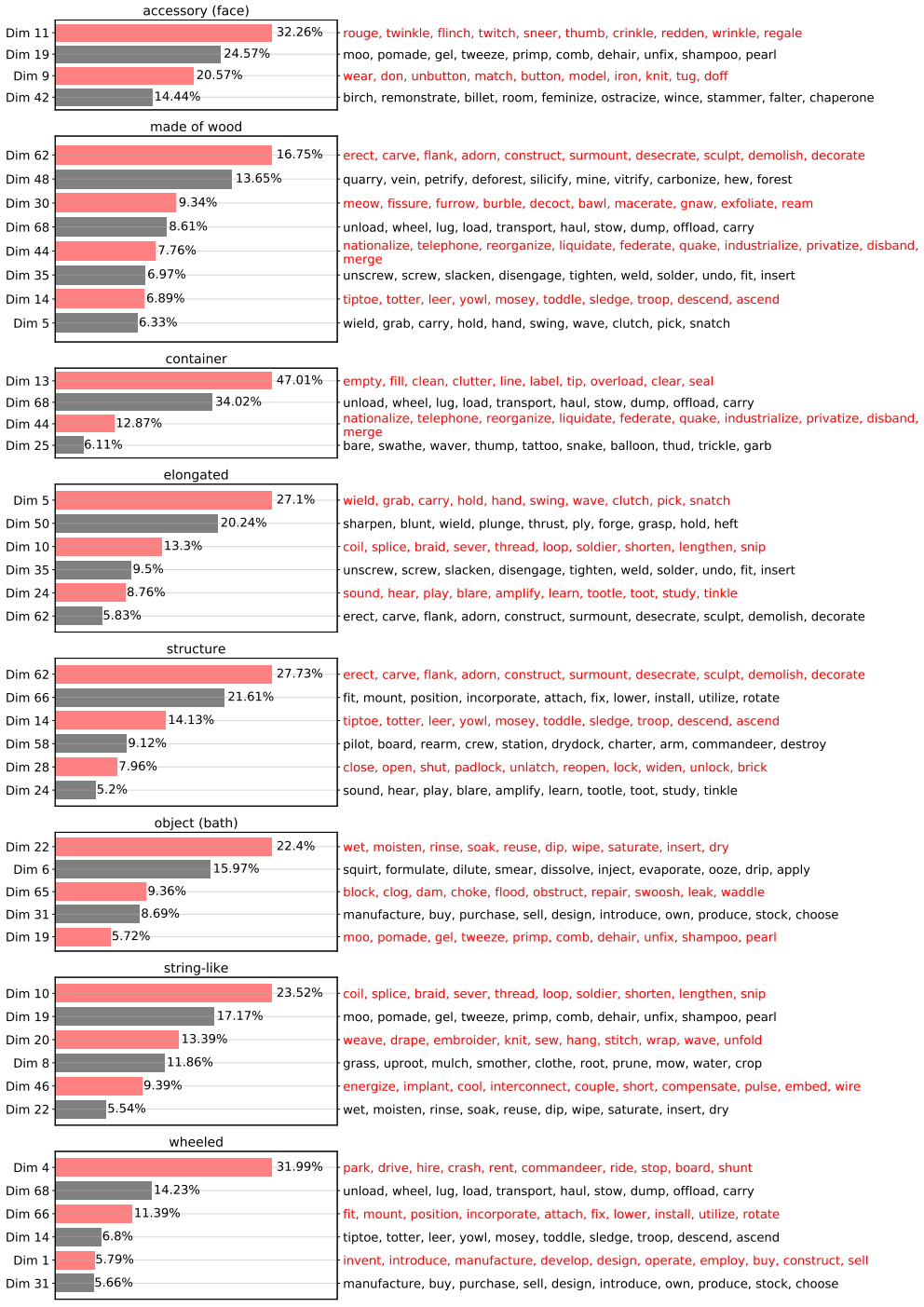

Figure 10: Components of SPoSE dimension approximation (D)

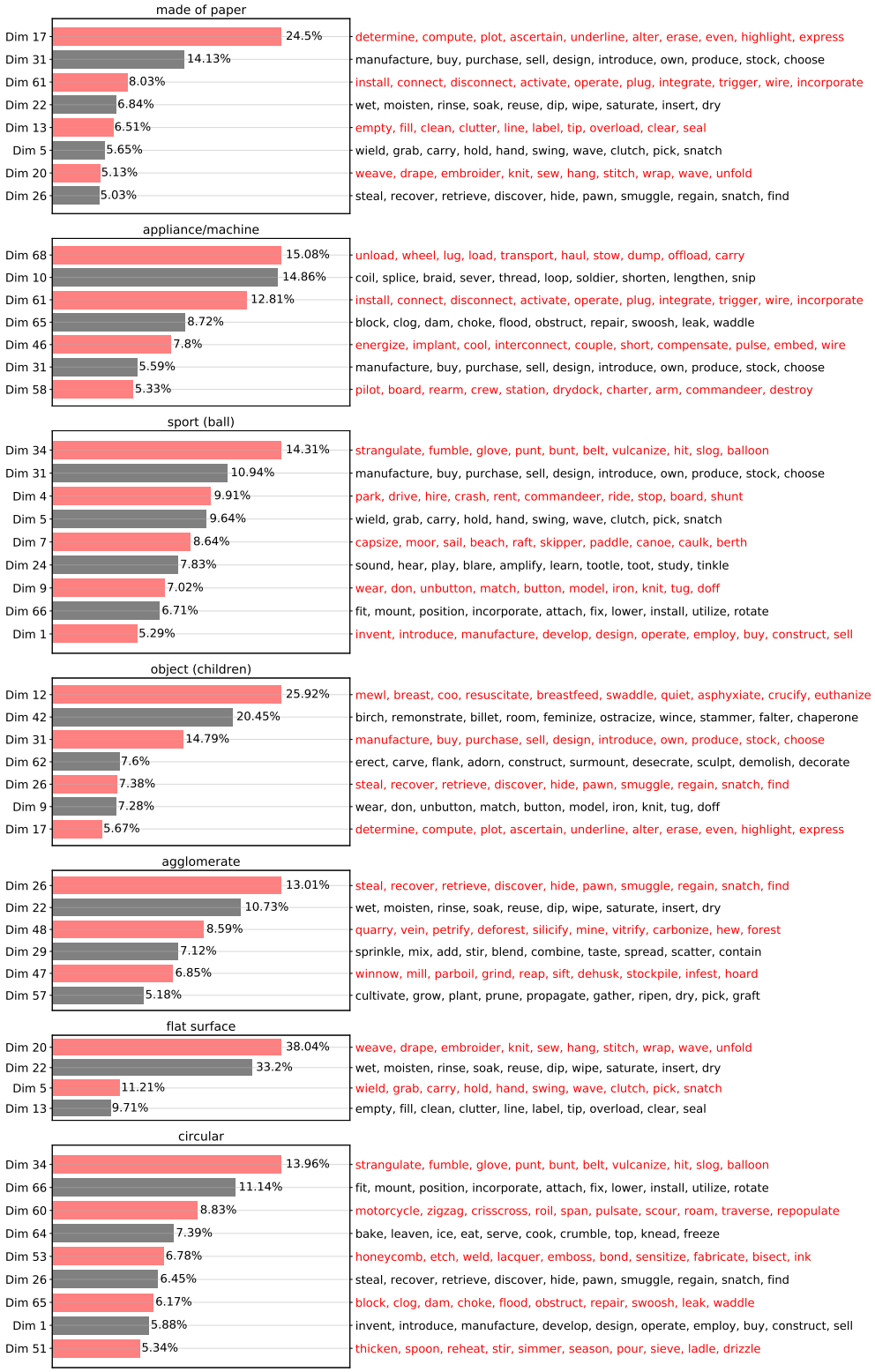

Figure 11: Components of SPoSE dimension approximation (E)

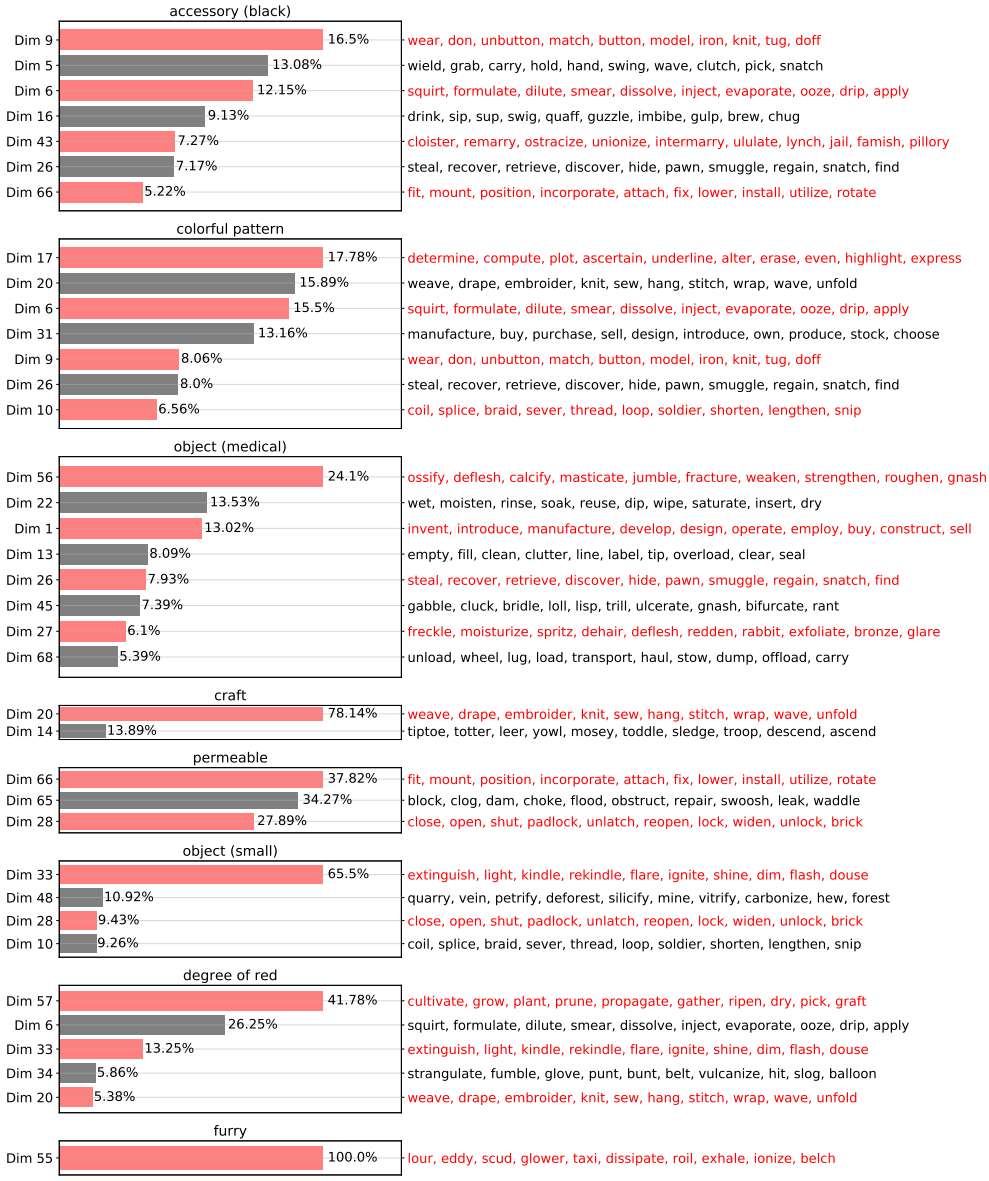

Figure 12: Components of SPoSE dimension approximation (F)