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Adaptations nutritionnelles à l'activité physique chez l'adolescent en situation d'obésité : implication du système cognitif

Maud Miguet

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SCIENCES ET TECHNIQUES DES ACTIVITÉS PHYSIQUES ET SPORTIVES

École doctorale des Sciences de la Vie, Santé, Agronomie, Environnement

THÈSE

En vue de l'obtention du grade de

DOCTEURE DE L'UNIVERSITÉ CLERMONT AUVERGNE

Adaptations nutritionnelles à l'activité physique chez l'adolescent en situation d'obésité : implication du système cognitif

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Présentée et soutenue publiquement par

Maud MIGUET

Le 21 octobre 2019

Devant le jury composé de

Pr Yves Boirie (PU-PH)	CHU de Clermont-Ferrand	Président
Dr Fabienne Mougin-Guillaume (MCF-HDR)	Université de Franche-Comté	Rapporteure
Dr Kristine Beaulieu (PhD)	Université de Leeds	Rapporteure
Pr Jean Michel Lecerf (PU-PH)	CHU de Lille	Examinateur
Dr David Thivel (MCF-HDR)	Université Clermont Auvergne	Directeur

« Eating alone will not keep a man well, he must also take exercise. For food and exercise, while possessing opposite qualities, yet work together to produce health. »

Hippocrate

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AgRP : Agouti-related peptide
AUC : Areas under curves
BMI : Body Mass Index
CART : Cocaine and amphetamine regulated transcript
CHO : Carbohydrates
CON : Condition contrôle
DE : Dépense énergétique
DEBQ : Dutch Eating Behaviour Questionnaire
DTE : Desire to eat
DXA : Dual energy x-ray absorptiometry
EE : Energy expenditure
EI : Energy intake
FFM : Fat free mass
FM : Fat mass
fMRI : Functional magnetic resonance imaging
GLP-1 : Glucagon-like peptide-1
HFSA : High fat savoury food
HFSW : High fat sweet food
HIIE : High intensity interval exercise
HIIT : High intensity interval training
IPAQ : International Physical Activity Questionnaire
Kcal : Kilocalorie
LFPQ : Leeds Food Questionnaire Preference
LFSA : Low fat savoury food
LFSW : Low fat sweet food
MICT : Moderate intensity continuous training
NPY : Neuropeptide Y
PA : Prise alimentaire
PFC : Prospective food consumption
POMC : Pro-opiomélanocortine
PYY : Peptide YY
REI : Relative enrgy intake
RER : Respiratory exchange ratio
RMR : Resting metabolic rate
SD : Standard deviation
TFEQ : Three-Factor Eating Questionnaire
VO2max : Volume d'oxygène maximum
α-MSH : Melanocyte stimulating hormone α

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Communications orales

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2. Impact d'un programme d'entraînement en mode excentrique dynamique sur la composition corporelle de l'adolescent en surpoids et obèse, *JFN 2017*, Valérie Julian, David Thivel, MAUD MIGUET, Bruno Pereira, Julianne Touron, Yves Boirie, Frédéric Costes, Emmanuel Coudeyre, Martine Duclos, Ruddy Richard

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1. When do health perceptions and liking drive children's food choices? The influence of context and weight status*, SSIB 2017,* Lucile Marty, MAUD MIGUET, Sophie Nicklaus, Stéphanie Chambaron, Sandrine Monnery-Patris

2. Effect of a 10-month multidisciplinary weight loss program on quality of life and health perception in adolescents with obesity, *ECO 2017,* Julie Masurier, MAUD MIGUET, Daniel Courteix, Yves Boirie, Martine Duclos, David Thivel

3. Moderate versus high intensity interval exercise trainings on energy intake and appetite feelings in adolescents with obesity, *ECO 2017,* MAUD MIGUET, Julie Masurier, Valérie Julian, Lore Metz, Elodie Chaplais, Charlotte Cardenoux, Yves Boirie, Martine Duclos, David Thivel

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6. Peut- on utiliser le Quotient de Satiété comme prédicteur de la prise alimentaire chez l'adolescent en situation d'obésité ? *JFN 2018,* Alicia Fillon, MAUD MIGUET, Marwa Khammassi, Julie Masurier, Martine Duclos, Yves Boirie, Angelo Tremblay, Vicky Drapeau, Marie-Eve Mathieu, David Thivel

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Introduction

En France, plus d'un enfant sur cinq est en surpoids (Matta et al., 2018). Développer des stratégies de perte de poids efficaces pour ces jeunes, avant que leur santé ne soit altérée, est une réelle nécessité. Les recommandations de la Haute Autorité de Santé sont formelles : il faut encourager les populations à augmenter leur niveau d'activité physique et à réduire le temps qu'elles consacrent aux activités sédentaires. Ces recommandations visent à diminuer la prévalence du surpoids, de l'obésité et des maladies non-transmissibles qui leurs sont associées. Les bénéfices de l'activité physique ne sont, en effet, plus à démontrer tant sur les paramètres physiologiques, psychologiques, que sociaux (Warburton et al., 2006). De plus, sur le plan calorique, la pratique physique permet d'accroitre la dépense énergétique et donc d'optimiser le bilan énergétique total (Wiklund, 2016).

Cependant, l'activité physique seule ne semble pas être une stratégie efficace pour induire une perte de poids (Swift et al., 2014). De nombreuses études montrent effectivement que la perte de poids induite par l'activité physique est souvent inférieure aux prévisions réalisées à partir de la balance énergétique (Dhurandhar et al., 2015). L'augmentation de la dépense énergétique induite par l'activité physique ne semble, en effet, pas suffisamment affecter le bilan énergétique final. Ces observations ont conduit à l'accroissement des travaux scientifiques questionnant plus précisément les effets de la dépense énergétique engendrée par l'exercice physique sur le bilan énergétique total. D'après la littérature, il semblerait qu'il existe des mécanismes compensatoires, mis en place en réponse à l'activité physique, dans le but de maintenir l'homéostasie et un poids stable (Doucet et al., 2018; Melanson et al., 2013). Parmi ces mécanismes, l'augmentation de l'appétit et/ou de la prise alimentaire post-exercice semble être une piste pertinente à explorer (King et al., 2008; Thomas et al., 2012).

Toutefois, les travaux conduits jusqu'alors se sont centrés sur des analyses de cohortes ou de populations, occultant la plupart du temps l'importante variabilité interindividuelle qu'il semble y avoir en réponse aux programmes d'activité physique. De plus, les résultats disponibles soulignent clairement le besoin de travaux de plus grande ampleur afin de mieux comprendre les mécanismes per- et post-intervention impliqués dans la perte et la reprise de poids. Enfin, alors que la littérature concernant les adaptations nutritionnelles à l'exercice chez l'adulte propose un nombre important d'études (pour revue voir Blundell et al., 2015), peu de données sont encore disponibles chez l'enfant et l'adolescent.

Face à ces constats, l'objet de ce travail doctoral sera d'investiguer les relations entre l'activité physique et les comportements alimentaires chez l'adolescent en situation d'obésité. Différentes modalités de pratique d'activité physique seront questionnées et les acteurs physiologiques et neurocognitifs impliqués dans la régulation de la prise alimentaire post-exercice seront explorés. Cette thèse s'inscrit à la croisée de quatre disciplines majeures de santé publique : l'activité physique, la nutrition, la physiologie et la psychologie. Ce travail multidisciplinaire apparait essentiel pour identifier et comprendre les réponses nutritionnelles à l'activité physique chez les jeunes en situation d'obésité, tentant d'apporter des éléments de réponse à cette problématique, afin d'optimiser les prises en charge.

PREMIÈRE PARTIE :

REVUE DE LA LITTÉRATURE

I. CONTROLE DU COMPORTEMENT ALIMENTAIRE

Les comportements alimentaires sont contrôlés de manière complexe et reposent sur un dialogue constant entre les organes périphériques et le système nerveux, qui intègre les stimuli qu'il reçoit en fonction de l'état nutritionnel et des habitudes alimentaires de l'individu. Ce contrôle est à la fois homéostatique et hédonique. À l'opposé de l'alimentation homéostatique, dirigée par les besoins métaboliques, énergétiques et nutritionnels et guidée par les sensations de faim, de rassasiement et de satiété ; l'alimentation hédonique dépend de facteurs sensoriels, émotionnels et motivationnels (renforcement ou récompense) et répond à des besoins affectifs et sociaux (Berthoud, 2011). De nombreuses recherches en biologie, neurophysiologie et biopsychologie ont permis d'identifier les acteurs majeurs impliqués dans le contrôle de la prise alimentaire et ont notamment mis en avant les axes intestin-cerveau et tissu adipeux-cerveau. D'après Hopkins et ses collaborateurs (Hopkins et al., 2000), le contrôle de la prise alimentaire s'établit sur trois niveaux : (1) psychologique et comportemental, (2) physiologique et métabolique, (3) neuronal.

Le contrôle de la prise alimentaire a longtemps été étudié de manière indépendante de la dépense énergétique. Cependant, l'augmentation constante de la prévalence du surpoids et de l'obésité au niveau mondial a orienté les professionnels de santé vers une approche plus globale de la balance énergétique en considérant ses deux composantes, la prise alimentaire (PA) et la dépense énergétique (DE), de manière intégrée. Les premiers résultats publiés considérant les potentielles interactions entre la PA et la DE datent des années cinquante. Mayer et al. avaient alors obtenu une relation linéaire entre la PA et la DE de travailleurs, avec une consommation de calories d'autant plus importante que le niveau d'activité physique était élevé (Mayer et al., 1956). Cependant, les auteurs avaient aussi décrit une zone de non-régulation dans laquelle une diminution de la DE n'était pas concomitante à une réduction de la PA. C'est en 1974 que John Taylor propose alors une relation en « J » entre PA et DE, relation confirmée depuis par plusieurs études et revues systématiques (Beaulieu et al., 2017; Hopkins et al., 2000), figure 1).

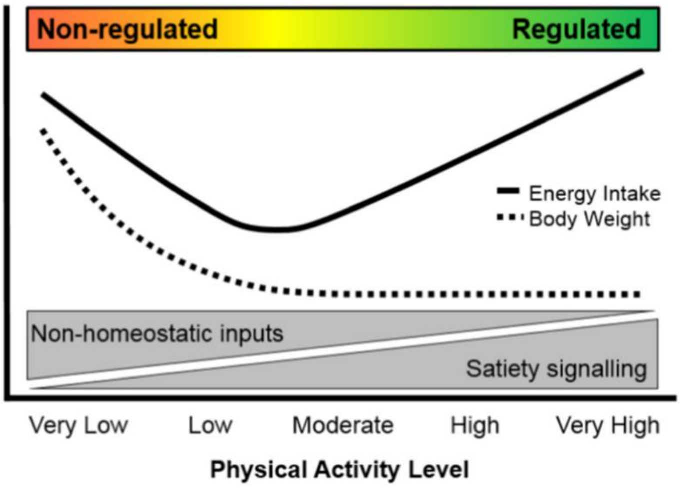


Figure 1 : Relation entre niveau d'activité physique et prise alimentaire d'après Beaulieu et al. 2017

Ainsi, à faible niveau d'activité physique, la prise alimentaire semble majoritairement sous le contrôle de facteurs hédoniques, favorisant une consommation énergétique excessive (et non adaptée aux dépenses), conduisant à une prise de poids. A l'inverse, à haut niveau d'activité physique, un contrôle homéostatique semble opérer, permettant une meilleure adéquation entre les dépenses et les apports, favorisant l'équilibre pondéral. Si les mécanismes expliquant cette relation sont encore en cours d'exploration à ce jour, plusieurs pistes ont déjà été investiguées soulignant entre autres le rôle de la composition corporelle et de la sensibilité individuelle aux signaux homéostatiques (hormonaux, métaboliques et nerveux). Par ailleurs, la réponse nutritionnelle immédiate à l'exercice physique aigu semble différer des adaptations chroniques. En effet, de nombreuses études ont démontré un effet anorexigène transitoire de l'exercice physique. Ainsi, de manière aiguë, l'exercice physique permettrait d'une part d'augmenter la DE et d'autre part de diminuer la sensation de faim et la prise alimentaire. Étudier et comprendre ces réponses nutritionnelles à l'activité physique chez des jeunes en situation d'obésité s'avère essentiel en vue d'améliorer nos stratégies de prise en charge.

II. EXERCICE PHYSIQUE AIGU

En 2004 est parue la première étude, à notre connaissance, évaluant l'impact de l'exercice physique aigu sur les comportements alimentaires chez l'enfant (Moore et al., 2004). Dans cette étude, des jeunes filles normo-pondérées (âgées de 9 à 10 ans) devaient réaliser trois conditions dans un ordre randomisé : une condition contrôle sans exercice, une condition exercice à faible intensité (50% de VO_2max) et une condition exercice à haute intensité (75% de VO_2max). La durée de l'exercice était calibrée pour entrainer la même dépense énergétique lors des deux conditions, soit environ 180 kcal. Durant les 3 journées expérimentales la prise alimentaire *ad libitum* était mesurée lors du déjeuner et du dîner (servis respectivement à 12h30 et 17h). Les résultats indiquent que la balance énergétique était significativement supérieure lors de la condition contrôle par rapport aux conditions avec exercice, suggérant que le déficit énergétique engendré par l'exercice physique n'entraine pas de mécanisme direct d'adaptation nutritionnelle.

Dans la suite de ces travaux, Bozinovski et al. ont questionné plus précisément l'effet du niveau de déficit énergétique (260 kcal *versus* 790 kcal) sur la PA de jeunes normo-pondérés âgés de 9 à 14 ans. Dans cette étude, une session de 15 minutes d'activité physique était comparée à une session de 45 minutes de pratique à même intensité (au premier seuil ventilatoire) sur la réponse nutritionnelle (Bozinovski et al., 2009). Les résultats indiquent que les sujets consomment la même quantité d'énergie (en kcal) au buffet *ad libitum* proposé 30 minutes après l'exercice, indépendamment de la durée de celui-ci ; suggérant ainsi que la dépense énergétique (260 *versus* 790 kcal) n'est pas le principal prédicteur de la PA post-exercice. Cette étude confirme les résultats précédemment obtenus par Moore et al., selon lesquels l'activité physique permettrait de modifier la balance énergétique en faveur d'un déficit énergétique, sans pour autant augmenter les sensations de faim et la PA. L'étude de Masurier et al., au design similaire, mais réalisée cette fois-ci auprès d'adolescents en situation d'obésité (âgés de 12 à 15 ans), indique également, qu'indépendamment de la durée de l'exercice (20 ou 40 minutes, réalisés au premier seuil ventilatoire), la PA *ad libitum* mesurée 30 minutes après n'est pas significativement différente de celle suivant la condition « contrôle » sans exercice (Masurier et al., 2018).

De manière intéressante, certains travaux ont interrogé les réponses nutritionnelles à l'exercice entre des jeunes normo-pondérés et des jeunes en situation d'obésité. Nemet et al. ont questionné l'effet d'exercices (1) en aérobie, (2) en résistance, et (3) en milieu aquatique, par rapport à une session sans exercice, sur les comportements alimentaires de jeunes âgés de 6 à 11 ans minces *versus* en surpoids (Nemet et al., 2010). Les résultats montrent que la PA post-exercice est affectée de manière différente chez les adolescents normo-pondérés par rapport aux adolescents en surpoids. En effet, l'exercice en résistance induit un effet anorexigène uniquement chez les jeunes normo-pondérés, tandis que la session aquatique a un effet orexigène chez les adolescents en surpoids (voir figure 2).

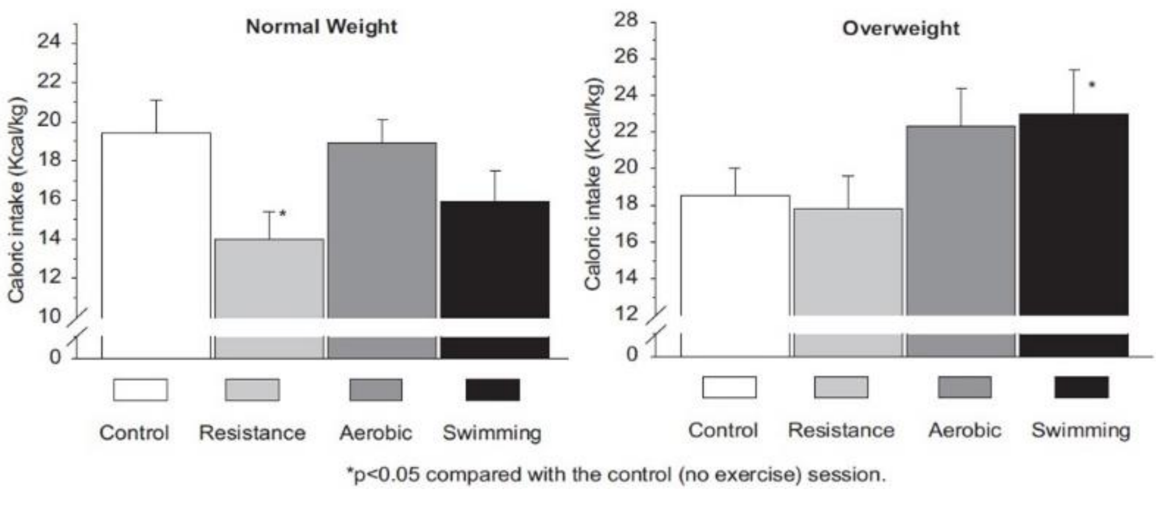
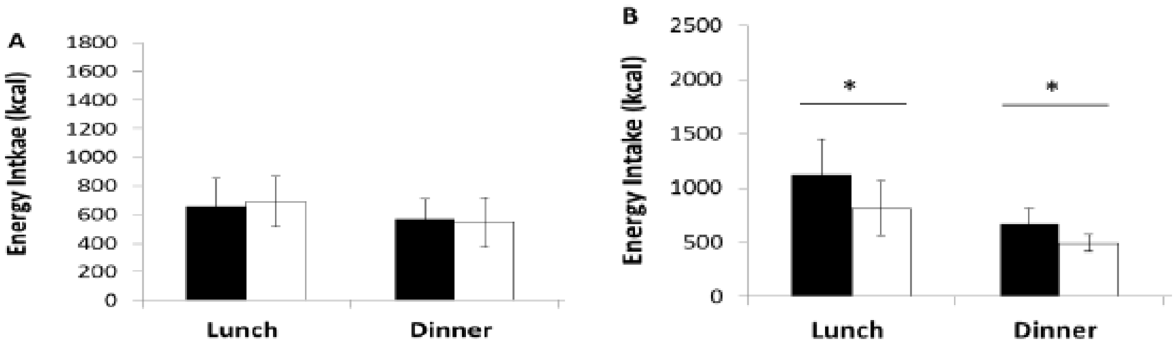


Figure 2 : Prise alimentaire en fonction du type d'exercice chez l'enfant mince et en surpoids d'après Nemet et al. 2009

Suite à ces travaux, Thivel et al. montrent également en 2014 que la réponse nutritionnelle à l'exercice semble dépendante du statut pondéral. En effet, cette étude, incluant des adolescents minces et en situation d'obésité (appariés pour leur âge et leur stade de développement), visait à questionner l'effet d'un exercice de 30 minutes réalisé à 75% de VO_2max sur la PA *ad libitum*, au déjeuner et au dîner, selon le statut pondéral. Les résultats indiquent une diminution de la PA suite à la session exercice par rapport à la session contrôle uniquement chez les adolescents en situation d'obésité, tandis que la PA *ad libitum* n'est pas affectée chez les adolescents normo-pondérés en réponse à l'exercice (Thivel et al. 2014, voir figure 3).



Adolescents minces | Adolescents en situation d'obésité

Figure 3 : Prise alimentaire *ad libitum* en session Contrôle (noir) *versus* Exercice (blanc) d'après Thivel et al. 2014

Finalement, la question du statut pondéral, dans les réponses nutritionnelles à l'exercice, a été investiguée dans une revue systématique et méta-analyse. Cette dernière combinait l'ensemble des études disponibles rapportant la PA *ad libitum,* immédiatement mesurée après une session expérimentale d'exercice physique chez des jeunes normo-pondérés et en situation d'obésité, âgés de 5 à 18 ans (Thivel et al., 2016). Les résultats des 14 études incluses, combinant près de 31 sessions expérimentales, indiquent qu'il n'y a aucun effet significatif de l'exercice sur la PA chez les enfants et les adolescents minces (pas de mécanisme compensatoire qui augmente la PA) alors que chez les enfants et adolescents en situation d'obésité, toutes conditions d'exercices confondues, une réduction significative de la PA post-exercice est mise en avant (figure 4). Ainsi, chez les adolescents en situation d'obésité, l'exercice physique aigu, induit d'une part une augmentation de la DE, mais également une diminution de la PA.

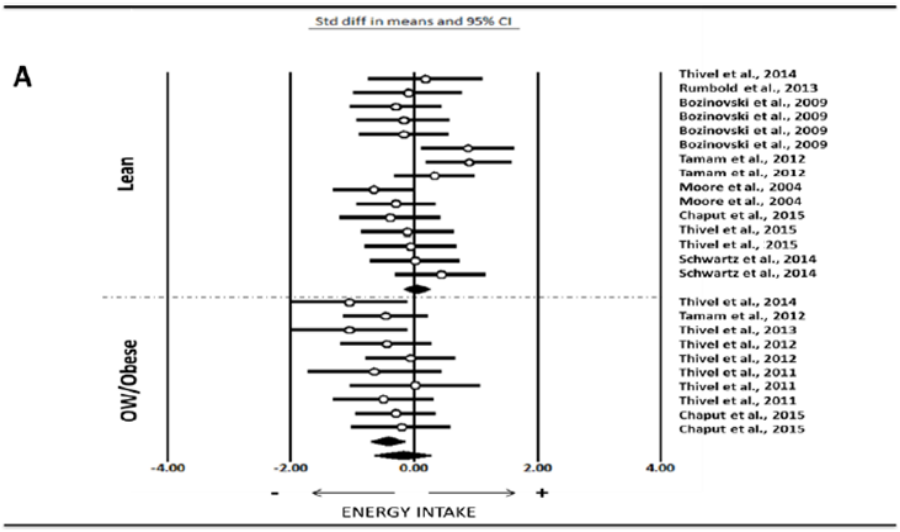


Figure 4 : Forest Plot de la prise alimentaire post-exercice chez des adolescents minces *versus* en situation d'obésité d'après Thivel et al. 2016

Toutefois, plusieurs articles et récentes revues ont souligné une grande variabilité interindividuelle dans la réponse nutritionnelle post-exercice (Thivel et al., 2013; Thivel et al., 2016), amenant certains auteurs à parler d'individus « répondeurs » en opposition aux « non-répondeurs ». De nombreuses interrogations persistent quant aux mécanismes permettant d'expliquer ces différences d'adaptations nutritionnelles entre personnes minces et en situation d'obésité. Ainsi, tant le rôle de la masse grasse que celui de la masse maigre ont été investigués dans les réponses nutritionnelles à l'exercice. Parmi les hypothèses avancées, le tissu adipeux, en tant que principale réserve d'énergie de l'organisme, pourrait favoriser la réduction de la prise énergétique post-exercice (Charlot & Chapelot, 2013). Si chez l'adulte les résultats ne semblent pas aller dans ce sens (Charlot

& Chapelot, 2013), chez l'enfant, cette piste parait pertinente. En effet, il semblerait que le niveau d'adiposité soit négativement corrélé à l'activation neuronale en réponse à des stimuli alimentaires après un exercice physique chez des adolescents en situation d'obésité (Fearnbach et al., 2016). Ainsi, plus le niveau de masse grasse est important moins l'activation neuronale face à des signaux alimentaires est grande après l'exercice. Les auteurs concluent que l'effet anorexigène de l'exercice retrouvé chez les adolescents en situation d'obésité pourrait être expliqué, en partie, par des différences dans le traitement cognitif des signaux relatifs à la nourriture, liées à leur important niveau de masse grasse, par rapport à des adolescents minces (Fearnbach et al., 2017). Ces résultats suggèrent qu'il existe une continuité dans la variabilité de la compensation, plutôt qu'une distinction dichotomique entre les adaptations nutritionnelles chez les minces d'un côté et chez les personnes en situation d'obésité de l'autre. Des études complémentaires sont toutefois nécessaires pour questionner l'impact du degré d'obésité dans la réponse nutritionnelle post-exercice.

Par ailleurs, le rôle de la masse maigre dans le contrôle de la PA a aussi été investigué ces dernières années. Les recherches actuelles concluent que la masse maigre est corrélée à la PA via le métabolisme de repos ; la masse maigre étant le principal déterminant de ce dernier (Blundell et al., 2012; chez l'adolescent obèse voir Cameron et al., 2016). A ce propos, Fearnbach et al. ont démontré, chez des enfants à risque de surpoids, que l'indice de masse maigre (en kg/m^2) était associée à la PA post-exercice, alors que cette association n'était pas retrouvée en condition contrôle (sans exercice) (Fearnbach et al., 2017), soulignant ainsi une meilleure régulation homéostatique après l'exercice. Dans cette dernière étude, la perception de l'effort réalisé était aussi corrélée à la PA post-exercice. En effet, pour chaque augmentation d'un point du niveau d'effort perçu sur l'échelle de Borg, les enfants augmentaient leur PA de 270 kcal (Fearnbach et al., 2017). En d'autres termes, plus les enfants trouvaient l'exercice difficile plus ils augmentaient leur prise alimentaire à la suite de celui-ci. Ainsi, tandis que les recherches investiguant le rôle du statut pondéral et du degré d'obésité demandent à être approfondies, il semble aussi nécessaire de questionner les caractéristiques de l'exercice proposé en tant que modulateur de la réponse nutritionnelle à l'exercice.

III. INTENSITE DE L'EXERCICE

Les opinions diffèrent quant à la modalité optimale de pratique pour induire une perte de poids durable chez des adolescents en situation d'obésité. En effet, de nombreux articles font l'état de l'efficacité de différents programmes d'entrainement, sans consensus (Liu, Zhu, & Deng, 2019). Les programmes d'exercice physique à intensité modérée, tout comme les exercices à haute intensité, présentent des avantages (Türk et al., 2017). Cependant, si les effets de ces deux modalités sont souvent comparés sur les paramètres cardiovasculaires, métaboliques, de la composition corporelle ou encore sur le niveau d'effort perçu ; leurs effets sur la prise alimentaire sont peu renseignés. Pourtant, questionner l'impact de différentes intensités d'exercice sur les adaptations nutritionnelles semble essentiel dans un objectif global de la gestion du poids, et donc de la prise en charge de l'obésité pédiatrique. Alors que quelques études avaient déjà été menées chez des adolescents minces, Thivel et al. sont les premiers à avoir questionné l'effet de l'intensité de l'exercice sur la PA chez des adolescents en situation d'obésité (Thivel et al., 2012).

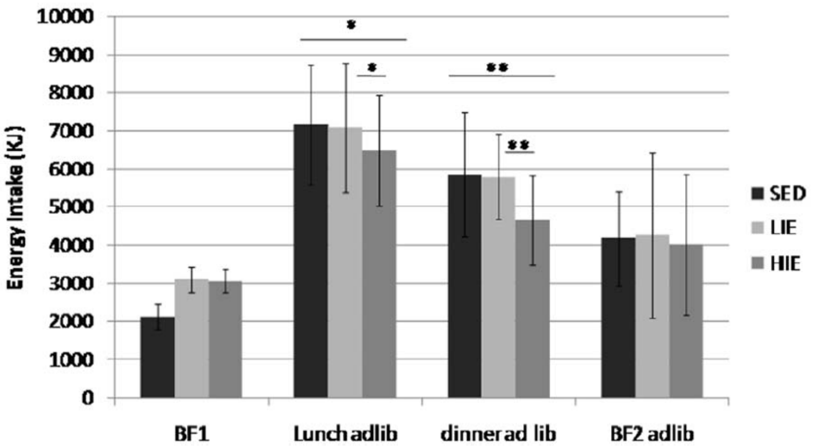


Figure 5 : Prise alimentaire (kcal) aux différents repas selon la condition (SED = sédentaire ; LIE = faible intensité ; HIE = haute intensité) Thivel et al. 2012

Dans cette étude, les adolescents ont participé à 3 conditions dans un ordre randomisé : une session contrôle (sans exercice), une session exercice à haute intensité (75% de VO_2max) et une session à faible intensité (40% de VO_2max). Les deux exercices étaient calibrés de manière à engendrer la même dépense énergétique (≈ 340 kcal). Comme nous pouvons le voir sur la figure 5, seule la séance à haute intensité a induit une diminution de la PA *ad libitum.* Cette réduction était significative aussi bien au déjeuner qu'au dîner suivant l'exercice à haute intensité. Ces résultats confirment l'effet différé que l'exercice physique peut avoir sur la PA, (précédemment démontré dans Thivel et al., 2011). Cependant, cet effet anorexigène est transitoire, puisqu'au petit-déjeuner du jour suivant, également servi *ad libitum,* aucune différence de PA n'était retrouvée entre les trois conditions. Au vu du nombre croissant de travaux dans ce domaine, une récente méta-analyse a questionné l'effet de l'intensité de pratique sur la PA auprès d'adolescents en surpoids et en situation d'obésité (figure 6, (Thivel et al., 2016)). Les analyses confirment que seuls les exercices de haute intensité (>70% VO_2max) ont un effet anorexigène sur la PA de ces derniers, renforçant ainsi l'intérêt de ce type de pratique pour modifier la balance énergétique, par rapport aux exercices d'intensité faible ou modérée.

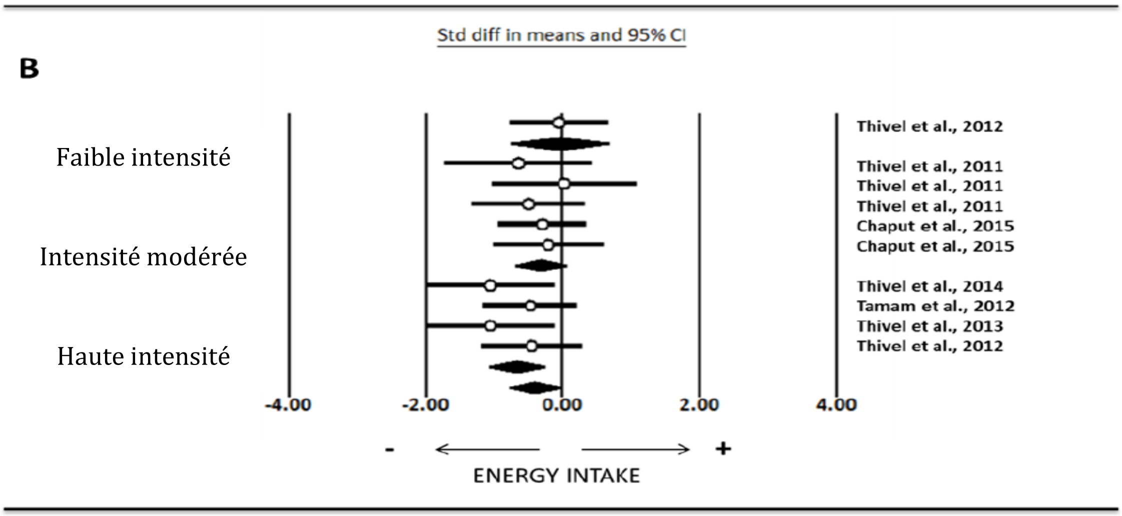


Figure 6 : Forest Plot de la prise alimentaire post-exercice chez des adolescents en situation d'obésité selon l'intensité d'après Thivel et al. 2016

Par ailleurs, l'exercice intermittent, pratique dans laquelle des périodes de travail intensives sont entrecoupées de périodes de travail à faible intensité, est une modalité d'entrainement en plein essor. Les intérêts et bénéfices de cette modalité de pratique sont en effet multiples. Le travail intermittent permet, pour un temps d'entrainement considérablement réduit, des améliorations égales, voir supérieures, de la composition corporelle, du métabolisme et des fonctions cardio-vasculaires par rapport aux modalités classiques d'entrainement (García-Hermoso et al., 2016). Chez l'adulte, il semblerait que l'exercice intermittent de haute intensité ait des effets similaires sur les sensations d'appétit et le système de la récompense alimentaire par rapport à un exercice d'intensité modérée (Alkahtani et al., 2013). Chez l'enfant, une seule étude a questionné l'effet du travail intermittent sur la PA, mais celle-ci a été menée chez des sujets minces (Moore et al., 2004). En accord avec la littérature, démontrant un effet « statut-pondéral dépendant », leurs résultats ne montrent aucun effet de l'exercice sur la PA. Cependant, la réponse nutritionnelle à l'exercice intermittent chez les adolescents en situation d'obésité n'est pas connue à ce jour et cela constitue une limite, qui a été soulignée dans la précédente méta-analyse. Afin d'améliorer nos connaissances sur la régulation de la balance énergétique, des études sont nécessaires pour évaluer la réponse nutritionnelle à cette modalité en plein essor.

Finalement, la revue de la littérature nous indique que l'exercice intense peut avoir un effet anorexigène transitoire chez les adolescents en situation d'obésité. Cependant, dans une dynamique de développement de nouvelles stratégies de traitement de l'obésité pédiatrique, la compréhension de ces mécanismes d'interaction lors d'une prise en charge chronique chez l'adolescent en situation d'obésité semble particulièrement importante.

IV. ACTIVITE PHYSIQUE CHRONIQUE

King et al. sont les premiers à avoir questionné l'effet d'une prise en charge résidentielle multidisciplinaire incluant de l'activité physique sur les sensations d'appétit chez des adolescents en situation d'obésité (King et al., 2007). Dans cette étude, les sensations de faim et de satiété ont été mesurées à l'aide d'échelles visuelles analogues électroniques, à intervalles réguliers tout au long de la journée, au début de la prise en charge et de la même manière au terme des 6 semaines de prise en charge. Le déficit énergétique était induit par un rééquilibrage calorique (entre 1300 et 3300 kcal par jour selon les besoins estimés) et par la pratique d'activité physique (6 heures par jour, combinant une séance en endurance, une séance aquatique, 2 sessions basées sur le jeu et 2 sessions au choix). Suite aux 6 semaines de prise en charge, les résultats montrent que la sensation de faim sur la journée (exprimée en aire sous la courbe) était significativement augmentée tandis que la sensation de satiété était significativement diminuée ; parallèlement à une réduction significative du poids. De manière similaire, la faim à jeun était significativement augmentée et la réponse satiétogène au repas standardisé était diminuée. Malheureusement, la prise alimentaire effective n'a pas été mesurée dans cette étude et les sensations d'appétit ne reflètent pas toujours la PA effective (Bilski et al., 2013). Il est donc impossible, au vu de cette seule étude, de conclure quant aux adaptations nutritionnelles après une prise en charge chronique par l'activité physique.

Quelques années plus tard, Carnier et al. ont comparé la réponse nutritionnelle à une prise en charge multidisciplinaire incluant de l'activité physique aérobie seule ou bien de l'activité physique aérobie couplée à un travail en résistance (Carnier et al., 2013). A la fin de la prise en charge de 12 mois (à raison d'une heure de pratique, 3 fois par semaine), la PA des adolescents (mesurée par des relevés alimentaires de 3 jours) était significativement réduite dans les deux groupes, d'environ 500 kcal (Carnier et al., 2013). De manière intéressante, bien qu'il n'y ait pas de différence dans l'évolution de la PA entre les deux groupes, la prise en charge combinant l'activité physique en aérobie et le travail en résistance augmentait significativement la sécrétion d'AgoutiRelated peptide (qui stimule l'appétit), tandis que la prise en charge en aérobie uniquement augmentait la sécrétion de l'hormone alpha-MSH (qui supprime l'appétit). D'autres études sont nécessaires pour confirmer ces résultats et l'utilisation de méthodes plus objectives de mesure de la prise alimentaire est un impératif.

Prado et al. ont aussi rapporté une diminution de la PA suite à 12 semaines d'activité physique de haute intensité chez des adolescents en situation d'obésité (Prado et al., 2015). Cependant, dans cette dernière étude, la PA était encore une fois évaluée à l'aide de relevés alimentaires, ce qui peut avoir altéré la validité des résultats. En effet, les enquêtes alimentaires, bien qu'utiles d'un point de vue clinique et épidémiologique, présentent de nombreuses limites (Naska et al., 2017). L'estimation des quantités représente une source majeure d'erreur dans le recueil de données, d'autant que certains contextes sociaux sont susceptibles d'influencer l'appréciation des apports énergétiques (Brown et al., 2016). Ainsi, dans les deux études citées précédemment, il est très probable que les adolescents aient sous-estimé leurs apports énergétiques en fin de cure. En effet, les sujets en situation d'obésité et ayant un comportement de restriction alimentaire ont tendance à répondre en fonction de ce qui est socialement bien perçu (Maurer et al., 2006). Ce phénomène de désirabilité sociale peut avoir influencé (de manière consciente ou non) la déclaration des apports alimentaires par les adolescents, ce qui a pu conduire à des erreurs importantes dans l'analyse des résultats. Cette limite a déjà été soulignée dans une récente méta-analyse questionnant l'effet de programmes d'activité physique, mis en œuvre dans le cadre de la prise en charge de l'obésité, sur la PA d'adolescents (Schwartz et al., 2017). D'après les 9 études incluses dans l'analyse, la PA des adolescents en situation d'obésité semble diminuer suite à un programme multidisciplinaire de perte de poids (Schwartz et al., 2017). Cependant, les auteurs mettent en avant le potentiel manque de fiabilité des études incluses. D'une part, l'hétérogénéité des protocoles et d'autre part, les biais dans la mesure de la PA, souvent considérée comme une variable secondaire et effectuée par relevé alimentaire, altèrent la robustesse des conclusions émises jusqu'à présent. La mesure précise des apports alimentaires représente un réel challenge. C'est un paramètre difficile à évaluer, mais essentiel pour apprécier l'effet des interventions de perte de poids sur les comportements alimentaires. Ainsi, la reproductibilité et la puissance de la mesure des apports alimentaires via la mise en place de buffets *ad libitum* sont discutées dans la littérature (Arvaniti et al., 2000; Gregersen et al., 2008; Venti et al., 2010). Si les buffets *ad libitum* apparaissent comme une mesure plus objective de la PA que les relevés de consommation, ils sont souvent composés d'un seul item, qui plus est très palatable (par exemple, de la pizza), pouvant ainsi favoriser une surconsommation et ne pas refléter le réel impact d'un stimulus (par exemple, un exercice physique) sur la réponse nutritionnelle. Par ailleurs, si les buffets proposant un nombre important d'items (>50) ont démontré leur reproductibilité, leur mise en place est coûteuse et engendre un gaspillage alimentaire important. Suite à ces constats, notre équipe de recherche a mis en place et validé une méthode standardisée, robuste et reproductible de l'évaluation de la prise alimentaire (Thivel et al., 2016). L'utilisation de cette méthode permettrait une mesure davantage représentative ainsi qu'une normalisation des résultats (entre le début et la fin de la prise en charge par exemple). Des études supplémentaires, utilisant des designs spécifiques et des méthodologies appropriées sont donc nécessaires pour évaluer l'effet de l'AP chronique sur la PA d'adolescents en situation d'obésité.

S'il n'est actuellement pas possible de conclure quant à l'effet de l'activité physique chronique sur les comportements alimentaires chez les jeunes en situation d'obésité dû à un faible nombre d'études et des protocoles inappropriés, certaines études ont commencé à questionner les possibles acteurs impliqués dans ces adaptations à l'exercice, tant aigu que chronique.

V. Processus physiologiques et neurocognitifs impliqués dans les adaptations nutritionnelles a l'exercice

Processus physiologiques

Blundell et al. sont les premiers à avoir proposé une description schématique des principaux mécanismes impliqués dans le contrôle de la PA en réponse à l'activité physique. Le modèle qu'ils ont proposé distingue les effets à court terme de l'exercice de ceux observés à plus long terme. A court terme, l'action de l'exercice sur la PA semble être principalement médiée par les réponses des hormones gastro-intestinales et leurs interactions avec l'hypothalamus. La PA est en effet régulée par de nombreux peptides, pour la plupart sécrétés par la paroi du tractus digestif, dont la concentration varie en réponse à l'exercice. Ainsi, la réduction de la PA post-exercice en aigu a été attribuée d'une part à l'augmentation des hormones anorexigènes et d'autre part à la baisse des hormones orexigènes (majoritairement la ghréline). En 2009, l'équipe de Ueda et al. a rapporté qu'une session d'une heure de bicyclette ergométrique à 50% de VO_2max induisait une augmentation des peptides YY_{3-36} et GLP-1 chez des adolescents, accompagnée d'une réduction de leur prise alimentaire, par rapport à une session contrôle sans exercice (Ueda et al., 2009). Les résultats de Prado et al., en 2014, confirment l'augmentation du peptide YY_{3-36} et la réduction de la prise alimentaire en réponse à un exercice de 30 minutes au seuil ventilatoire chez l'adolescent en situation d'obésité (Prado et al., 2014). De manière intéressante, l'augmentation du peptide YY_{3-36} post-exercice semble être dépendante de l'intensité de pratique, avec des exercices à haute intensité induisant une augmentation supérieure de sa concentration, par rapport aux exercices à faible ou à intensité modérée (Ueda et al. 2009 ; Hazell et al. 2017). Ce résultat est en accord avec l'effet intensité-dépendant de l'exercice sur la PA. De nombreuses études ont aussi porté sur la variation de la concentration de la ghréline, « l'hormone de la faim », suite à l'exercice physique (Schubert et al., 2014 ; Douglas et al., 2016). Ainsi, en aigu, l'exercice semble induire une diminution de sa forme acylée, qui est biologiquement active, autant chez l'adolescent (Hunschede et al., 2017) que chez l'adulte situation d'obésité (figure 7, Douglas et al., 2016)

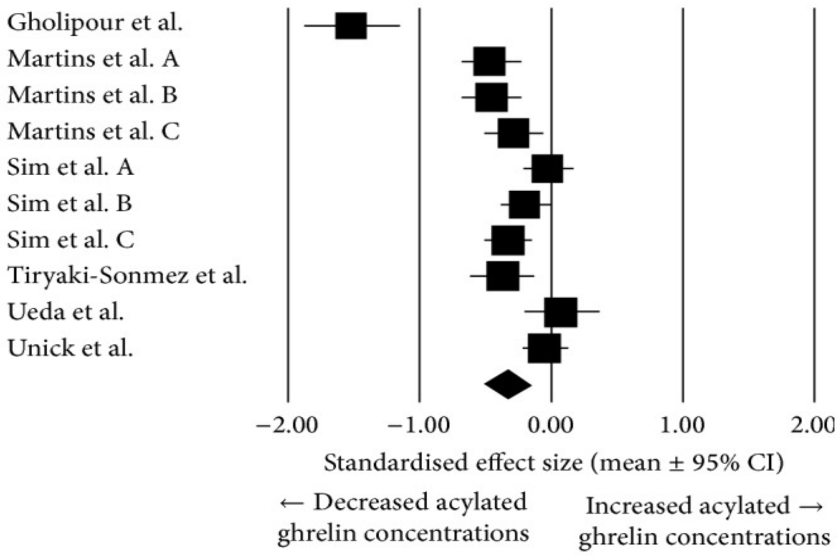


Figure 7 : Graphique en forêt de l'effet de l'exerice sur la concentration de la ghréline acylée chez des sujets en situation d'obésité d'après Douglas et al. 2016

En revanche, en réponse à l'activité physique chronique, il semblerait plutôt que la ghréline augmente tandis que les hormones de la satiété diminuent. En effet, il semblerait que la réduction de la balance énergétique, induite tant par la restriction calorique que par l'activité physique, augmente les niveaux de ghréline plasmatique (Foster-Schubert et al., 2005). Chez des adolescents en situation d'obésité, Gueugnon et al. observent une augmentation de la concentration plasmatique de ghréline à jeun après 9 mois de prise en charge multidisciplinaire (Gueugnon et al., 2012), accompagnée d'une absence de modification des taux de PYY, suggérant ainsi une augmentation de la prise alimentaire, qui n'a cependant pas été évaluée dans cette dernière étude.

A plus long terme, les études sur la régulation de la PA post-exercice ont questionné le rôle de la leptine et plus largement de la composition corporelle. Reflet de la variation des stocks énergétiques, la sécrétion de la leptine est proportionnelle au tissu adipeux (Considine et al., 1996). Ainsi, la perte de masse grasse observée en réponse à un programme d'activité physique s'accompagne d'une diminution des concentrations de leptine. Or cette hormone a une action inhibitrice de la PA d'une part, et stimulatrice de la dépense énergétique d'autre part (Pandit et al., 2017). Ainsi, de précédentes études ont démontré que la diminution des taux de leptine en réponse à une perte de poids constituait un facteur prédicteur de reprise de poids sur le long terme (Ahima, 2008; Erez et al., 2011), médiée en partie par l'augmentation de la PA.

Par ailleurs, les recherches actuelles concluent que la masse maigre, étant le principal déterminant du métabolisme de repos, est également un acteur déterminant du contrôle de la PA (Dulloo et al. 2018). Ainsi, la variation de la masse maigre a été associée à des fluctuations de la prise alimentaire (Stubbs et al., 2004). D'une part, la perte de masse maigre, résultant d'une periode de balance énergétique négative et entraînant l'abaissement du métabolisme de repos, est associée à une augmentation de l'appétit et de la prise alimentaire (figure 8).

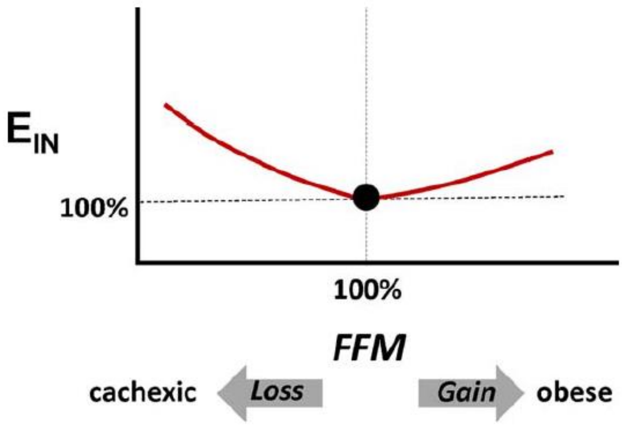


Figure 8 : Impact de la variation de masse maigre (FFM) sur la prise alimentaire (E_{IN}) d'après Dulloo 2017

Certaines études suggèrent d'ailleurs que la perte de masse maigre durant la perte de poids prédit la reprise de poids à l'issue de la phase interventionnelle. D'autre part, l'augmentation de la masse maigre (associée à une prise de poids ou a une pratique élevée d'activité physique) a également été associée à une augmentation de la prise alimentaire (figure 8). Chez l'adolescent en situation d'obésité cette association entre masse maigre et prise alimentaire a aussi été rapportéé par Cameron et al. d'après un large échantillon (n=304) (Cameron et al., 2016). Concernant plus précisement l'impact de la masse maigre sur la prise alimentaire post-exercice, comme précedement évoqué, Fearnbach et al. rapportent que, chez l'enfant à risque de surpoids, la masse maigre est associée de manière positive à la PA post-exercice (Fearnbach et al., 2017)

Enfin, au niveau central, plusieurs zones ont été impliquées dans la régulation de la PA post-exercice. D'une part, les populations neuronales NPY/AgRP aux effets orexigènes, et d'autre part, les POMC/CART aux effets anorexigènes assurent l'homéostasie énergétique (Schwartz et al., 2000). Leur synthèse et leur libération sont régulées par des facteurs hormonaux tels que l'insuline, la leptine, la ghréline et les glucocorticoïdes. L'étude de Carnier et al. a rapporté que 12 mois de prise en charge par l'activité physique (une heure 3 fois par semaine d'activité physique aérobie seule ou couplée à un travail en résistance), chez l'adolescent en situation d'obésité, induisait des modifications dans la concentration de ces neuropeptides (Carnier et al., 2013). Les conclusions de leur travail tendent à favoriser l'exercice en aérobie par rapport à l'exercice en résistance, dans le but de perdre du poids. L'exercice en résistance étant, en effet, responsable de l'augmentation du neuro peptide AgRP qui est un facteur orexigène (Carnier et al., 2013). Toutefois, ces résultats sont à considérer avec précaution. Effectivement, les dosages réalisés dans cette étude ne sont que le reflet plasmatique de la concentration au niveau neuronal.

Finalement, si le modèle physiologique proposé par Blundell et al. en 2016 (figure 9) semble synthétiser l'ensemble des connaissances scientifiques actuelles sur les mécanismes physiologiques impliqués dans les réponses nutritionnelles à l'exercice physique chez l'adulte, son application chez l'adolescent en situation d'obésité reste incertaine et de nombreuses pistes restent à être explorer chez cette population.

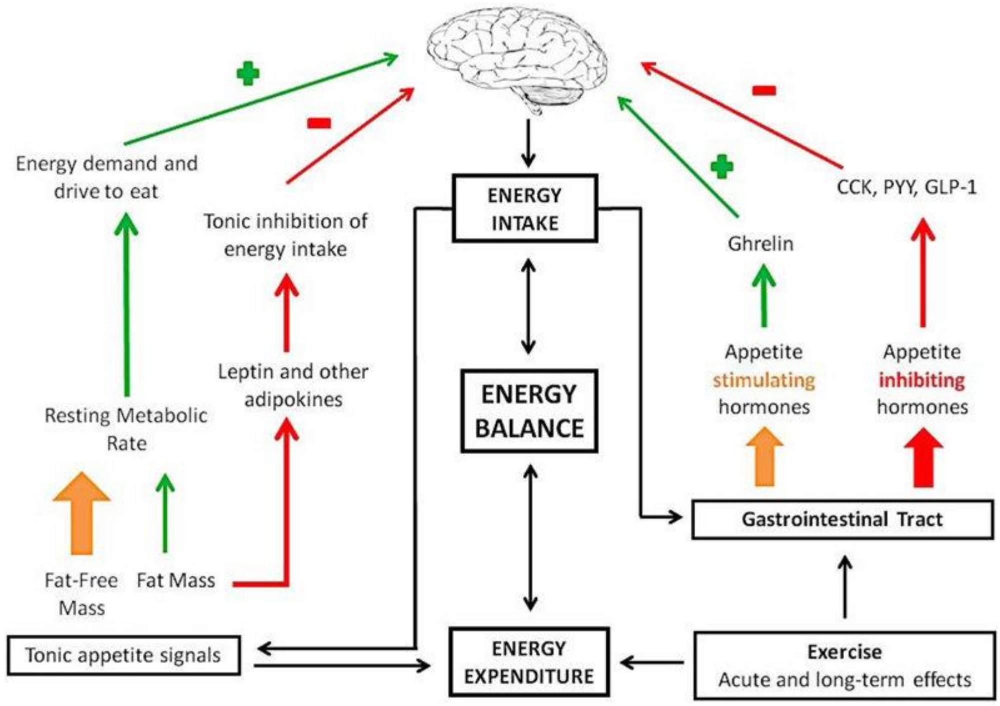


Figure 9 : Régulation de la prise alimentaire d'après Blundell et al. 2016

Par ailleurs, dans l'environnement actuel dit « obésogène », les signaux hédoniques semblent jouer un rôle particulièrement important dans la régulation de la prise alimentaire, pouvant surpasser l'influence des acteurs physiologiques homéostatiques.

Processus neurocognitifs

Les réponses nutritionnelles à l'exercice précédemment décrites pourraient aussi être expliquées par des modifications de la régulation neurocognitive et hédonique de la PA. Pour rappel, la régulation de la PA s'effectue sur trois niveaux (1) physiologique et métabolique, (2) neuronal, (3) psychologique et comportemental (Hopkins et al., 2000). Dans la partie précédente nous avons décrit les modifications physiologiques et métabolique engendrées par l'activité physique pouvant être impliquées dans la réponse nutritionnelle post-exercice. Nous allons désormais questionner les niveaux neuronal, comportemental et psychologique impliqués dans la régulation de la prise alimentaire, et leurs réponses à l'exercice.

1. Niveau neuronal

Les deux systèmes du contrôle de la PA, homéostatique et hédonique, fonctionnent en parallèle et veillent à assurer les niveaux énergétiques requis pour le bon fonctionnement de l'organisme. Le contrôle hédonique de la prise alimentaire, impliquant les processus de plaisir et de récompense, s'effectue dans les « hedonic-hotspots ». Dans de rares cas, un dysfonctionnement du système homéostatique (comme un déficit congénital en leptine par exemple) peut être à l'origine du développement d'une obésité ; toutefois l'omniprésence dans notre environnement d'aliments riches en énergie et hyper-palatables tend à augmenter la part du système hédonique dans le contrôle des comportements alimentaires. Ainsi, l'hyper-sollicitation du circuit de la récompense alimentaire, dit « Food Reward », peut être à l'origine d'une amplification de la motivation à manger et d'une diminution des signaux de satiété, aboutissant à une consommation énergétique excédant les réels besoins de l'organisme. Mieux comprendre cette régulation hédonique de la prise alimentaire s'avère essentiel pour développer des stratégies de gestion du poids efficaces.

Des études en neuro-cognition montrent une diminution de l'activité des zones cérébrales impliquées dans le système de la récompense alimentaire en réponse à l'exercice. En effet, chez l'adulte, Evero et al. ont par exemple montré une diminution de l'activité cérébrale (relevée par imagerie par résonnance magnétique fonctionnelle) dans les zones du traitement, de l'attention et de la motivation en réponse à des stimuli alimentaires, suite à un exercice physique d'une heure à haute intensité (Evero et al., 2012). Dans cette étude, la diminution de l'activité cérébrale en réponse aux stimuli alimentaires post-exercice était concomitante à une réduction des sensations de faim et de la propension à manger. De manière similaire, Hanlon et al. rapportent qu'une session d'exercice de 45 minutes à intensité modérée induit une diminution de l'amplitude de l'onde « late positive potential » en réponse aux stimuli alimentaires, indépendamment du statut pondéral (Hanlon et al., 2012). Ce résultat semble indiquer que la motivation à manger est diminuée en réponse à l'exercice. A plus long terme, Cornier et al. ont questionné l'effet d'une prise en charge de 6 mois par l'activité physique chez des adultes en surpoids sur la réponse neuronale aux stimuli alimentaires (Cornier et al., 2012). Les résultats montrent une réduction de l'activation neuronale, principalement dans la partie postérieure du cortex, qui est impliquée dans l'attention. De plus, la réduction de l'activité neuronale en réponse aux stimuli alimentaires en fin de cure était positivement corrélée à la réduction de la masse grasse et du poids (voir figure 10). Toutefois, dans ces deux études la PA effective n'était pas mesurée. Il est donc impossible de conclure si l'altération de l'activité neuronale post-exercice peut expliquer les réponses nutritionnelles observées dans d'autres études.

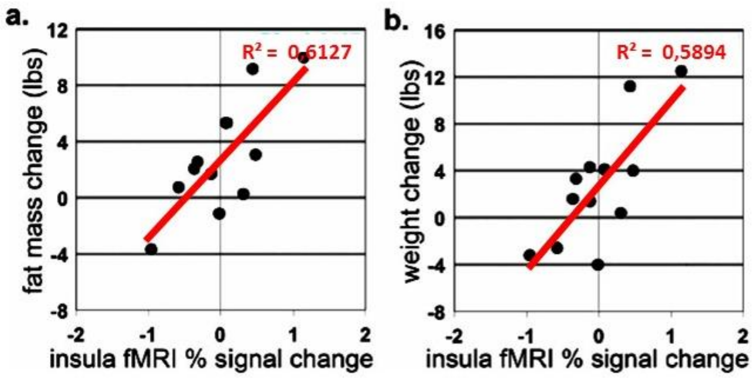


Figure 10 : Corrélation entre la réponse neuronale aux stimuli alimentaires et la perte de masse grasse (a) et de poids (b) suite à 6 mois de prise en charge interventionnelle par l'activité physique d'après Cornier et al. 2012

Plus récemment, Fearnbach et al. ont mené plusieurs études auprès d'adolescents en situation d'obésité et leurs résultats indiquent aussi une diminution de l'activation neuronale en réponse à des stimuli alimentaires après un exercice physique. En outre, les auteurs retrouvent une corrélation négative entre le niveau de masse grasse et l'activation neuronale post-exercice (Fearnbach et al., 2016), susceptible d'expliquer l'effet anorexigène de l'exercice retrouvé chez les adolescents en situation d'obésité, et non chez les sujets minces. Ces résultats pourraient suggérer une diminution de l'activation du système de la récompense en réponse à l'exercice chez les adolescents en situation d'obésité. Toutefois, aucune étude à ce jour n'a permis d'établir un lien entre la mesure objective de l'activation neuronale et la mesure subjective du Food Reward, via des tâches comportementales, et *in fine* de la PA.

Précédemment décrit par Berridge, il est maintenant bien établi que le circuit de la récompense est constitué de deux composantes : une composante affective et une composante motivationnelle (Berridge & Kringelbach, 2015). Le « liking » (composante affective) correspond au plaisir procuré par un aliment pour ses propriétés sensorielles et affectives. Au niveau neuronal, l'expression du liking est médiée principalement par les opioïdes. Le « wanting » (composante motivationnelle) correspond à l'intensité de la motivation ou le désir pour obtenir un aliment particulier. Le wanting est médié principalement par le système dopaminergique. Dans la vie quotidienne, ces deux composantes agissent la plupart du temps en synergie. Toutefois, la recherche expérimentale a permis de montrer que des aliments pouvaient avoir un impact uniquement sur l'une ou l'autre des composantes, car elles dépendent de systèmes cérébraux relativement distincts (Peciña et al., 2006). Ces mécanismes de renforcement ou de récompense ne sont pas toujours conscients. En effet, le liking qui relève du plaisir ressenti vis à vis d'un aliment est conscientisable et verbalisable. Le wanting, en revanche, n'a parfois pas d'explication verbalisable (« il fallait que je le mange ! »). Cette composante s'exprime alors à un niveau dit implicite (Berridge, 2004). Il est important de distinguer les deux facteurs du Food Reward et leur niveau d'activation ainsi que de les mesurer séparément au niveau comportemental. En effet, cela pourrait nous aider à déterminer leurs implications respectives et leur rôle dans la surconsommation ou la prise de poids.

2. Niveau comportemental

Au niveau neurobiologique le fonctionnement du Food Reward est aujourd'hui bien documenté, cependant son implication au niveau comportemental reste encore peu investiguée. En effet, le liking et le wanting ont souvent été étudiés en tant que processus neuronaux, puis rapportés à des mesures subjectives des sensations d'appétit et des comportements alimentaires tels que les choix alimentaires ou la PA. Toutefois, le lien entre les niveaux neuronal et comportemental est loin d'être parfaitement compris à ce jour (Finlayson & Dalton, 2012). En effet, certaines études rapportent une forte corrélation entre la mesure objective de l'activation du système de la récompense au niveau neuronal et la PA effective, tandis que d'autres ne trouvent pas d'association (Nijs et al., 2010; Stice et al., 2008; Stice et al., 2009). C'est en réponse à cette problématique, et dans le but de mesurer la dimension comportementale du Food Reward que de nouveaux outils de mesure ont été développés. Les mesures explicites du liking et du wanting sont le plus souvent réalisées à l'aide d'outils psychométriques tels que les échelles visuelles analogues. Afin de mesurer le liking explicite et le wanting explicite, des aliments sont présentés (aliments réels, en image ou sur ordinateur) aux participants qui sont amenés à répondre respectivement aux questions « combien aimez-vous cet aliment ? » et « à quel point désirez-vous cet aliment ? » sur des échelles allant généralement de « pas du tout » à « énormément ». Bien que ces mesures peuvent être sujettes au biais de la désirabilité sociale, elles sont très sensibles aux manipulations expérimentales. En effet, le liking et le wanting explicites différèrent entre l'état nourri et l'état à jeun, ils sont sensibles et permettent de mesurer des catégories particulières d'aliments, qui s'opposent en terme de goût et de teneur en gras. De plus, plusieurs études ont montré que le liking et le wanting explicites étaient des prédicteurs de la PA (Epstein et al. 2011; Mela, 2006; Temple et al., 2008). Enfin, ces mesures d'auto-évaluation sont faciles à réaliser et nécessitent peu de temps et d'efforts de la part des participants. En revanche, comme précédemment évoqué, le wanting peut être difficile à verbaliser. En effet, si les participants n'ont pas de mal à estimer à quel point ils aiment un aliment, ils sont souvent incapables d'évaluer avec précision leur désir implicite pour ce même aliment. En somme, il se trouve que plus la méthode de mesure requiert des réponses spontanées, plus elle renseigne la réelle motivation des participants envers un aliment, sans contamination des processus explicites (Finlayson et al., 2007). Ainsi, ces dernières années, diverses techniques de mesure ont été adaptées ou développées pour évaluer la dimension implicite du wanting. Ces méthodes impliquent généralement des tâches comportementales, telles qu'exécuter un clic sur une souris d'ordinateur, presser un bouton ou encore serrer un appareil de force, en relation avec la présence de stimuli alimentaires (images ou aliments réels). Ce type de mesure reflète la volonté du sujet et sa motivation pour obtenir l'aliment proposé (aliment à forte valence hédonique), autrement dit, à quel point le sujet est prêt à travailler, ou fournir un effort, pour avoir accès à cet aliment. D'autres méthodes se sont basées sur le temps de réaction comme indicateur de la réactivité et de l'attention pour refléter le wanting implicite pour un type d'aliment particulier (item cible) en comparaison avec d'autres aliments ou des « non-aliments » (items non-cibles) (Nathan et al., 2012). Des tâches visuelles attentionnelles telle que le Oddball paradigme, le Dot-probe paradigme ou encore l'effet Stroop sont utilisées pour mesurer le temps de réaction entre le stimulus et la réponse motrice, qui se traduit comme une mesure de la valeur motivationnelle (Nathan et al., 2012). Plus récemment, Finlayson et al. ont proposé une méthode d'évaluation du wanting implicite basé sur une procédure de choix forcé. Ce test permet donc, d'une part, d'évaluer la préférence relative pour un type d'aliment par rapport aux autres aliments et d'autre part le mesurer le wanting implicit (Finlayson et al., 2007).

Finalement, de nombreuses études ont questionné l'implication du liking et du wanting dans le développement du surpoids, de l'obésité et de certains troubles du comportement alimentaire et il apparait qu'un dérèglement du circuit de la récompense (tant son augmentation que sa diminution) n'est pas sans conséquence sur la PA (Berridge, 2009). Les recherche suggèrent que les personnes en surpoids ont un wanting plus élevé que les personnes normo-pondérées (Berridge, 2009). Ainsi, les sujets en situation d'obésité seraient prêts à travailler davantage pour obtenir une récompense alimentaire, plutôt que pour avoir accès à d'autres activités comme la lecture ou encore le jeu sur ordinateur, par rapport aux sujets normo-pondérés (Saelens & Epstein, 1996). En 2009, Hill et al. ont aussi montré que le wanting implicite pour des gâteaux prédisait la prise de poids sur un an chez des enfants de 7 à 10 ans ; la valeur réconfortante des gâteaux étant corrélée à la prise de poids et de masse grasse chez ces enfants (Hill et al., 2009).

Néanmoins, de récentes études suggèrent que l'activité physique pourrait modifier la valeur réconfortante de la nourriture en agissant tant sur le liking que le wanting. La place de l'activité physique dans la prise en charge et le traitement de l'obésité se justifie alors d'autant plus, du fait de son effet sur la dépense énergétique d'une part, et de son effet sur la régulation du comportement alimentaire d'autre part. En 1998, Lluch et al. avaient déjà questionné l'effet d'une session d'exercice (50 minutes à 70% de VO_2max sur bicyclette ergométrique) sur la motivation à manger, la PA effective et le plaisir de manger, mesurés après un repas *ad libitum* (Lluch et al., 1998). Leurs résultats montrent que l'exercice n'induit pas de modification de la PA mais augmente la valeur hédonique des aliments non gras après le repas *ad libitum.* Le résultat observé dans cette étude est encourageant puisqu'il suggère que l'activité physique augmente le plaisir de manger sans nécessairement augmenter la PA effective. De manière intéressante, Finlayson et al. ont montré que l'augmentation de la PA post-exercice, mise en avant dans leur étude, était associée à une augmentation du wanting implicite. Leurs résultats semblent ainsi indiquer que certaines personnes pourraient être résistantes à la perte de poids induite par l'activité physique, en raison d'une prédisposition à compenser la dépense énergétique, par le biais de l'augmentation du wanting implicite post-exercice (Finlayson et al., 2009). Au contraire, McNeil et al. trouvent que le Food Reward diminue en réponse à l'exercice (McNeil et al., 2015). En effet, dans cette étude les participants devaient réaliser trois conditions : une condition contrôle sans exercice, un exercice d'endurance et un exercice de résistance (calibrés de manière à induire la même dépense énergétique) dans un ordre randomisé. Leurs résultats indiquent d'une part une diminution de la préférence relative pour les aliments gras, par rapport aux aliments non-gras, après les 2 sessions exercice, comparativement à la session contrôle. D'autre part, le liking explicite pour les aliments gras était significativement réduit après l'exercice en résistance par rapport à la session contrôle (McNeil et al., 2015).

Finalement, à ce jour chez l'adulte une dizaine d'études seulement a questionné l'effet de l'exercice aigu sur le Food Reward (Alkahtani et al., 2013; Farah et al., 2012; Finlayson et al., 2009; Lluch et al., 1998; Lowe et al., 2016; Martins et al., 2015; McNeil et al., 2015; Taylor & Oliver, 2009; Thivel et al., 2018). Cependant, ces études emploient des méthodologies très variées, tant dans la mesure du Food Reward que dans le type d'exercice proposé, il est donc difficile de conclure quant à l'effet de l'exercice sur le Food Reward. En ce qui concerne la pratique régulière d'activité physique, une récente revue systématique, questionnant l'effet de la perte de poids sur le Food Reward, semble indiquer que les interventions de perte de poids, incluant de l'activité physique régulière, induisent une diminution du liking et du wanting pour les aliments riches en énergie (Oustric et al., 2018). Trois études ont aussi conclu que la diminution du Food Reward était associée à l'amélioration du poids chez ces adultes en situation d'obésité (Blundell et al., 2017; McVay et al., 2016; Stice et al., 2017). Toutefois, l'association entre l'exercice, le Food Reward et la gestion du poids se doit d'être clarifiée dans cette population.

3. *Niveau psychologique*

Il est aujourd'hui bien établi que le contrôle de la PA est aussi modulé par des facteurs psychologiques. En effet, l'état cognitif de l'individu (son humeur, ses émotions, la mémoire d'expériences antérieures) agit sur ses comportements alimentaires, en renforçant, ou, au contraire, en diminuant les signaux homéostatiques contrôlant la balance énergétique (Singh, 2014). Ce ne sont alors plus les sensations de faim et les besoins énergétiques qui contrôlent la PA mais des facteurs psychoaffectifs, ce qui peut favoriser la perte de contrôle et des épisodes de frénésies alimentaires. Mieux comprendre les déterminants et les implications de ces épisodes d'hyperphagie pourrait nous aider à expliquer la variabilité interindividuelle dans la réponse aux programmes de perte de poids et à l'activité physique. Par exemple, les résultats de l'étude d'Emery at al. (Emery et al., 2016) semblent indiquer que des femmes en situation d'obésité, et présentant des troubles hyperphagiques, ont tendance à mettre en place des mécanismes dits « compensatoires » afin d'abaisser leur dépense énergétique post-exercice. En effet, l'étude rapporte qu'après une séance d'exercice physique, cette population diminue significativement son niveau d'activité physique et augmente le temps consacré aux activités sédentaires. Ainsi, tandis que les femmes en situation d'obésité ne présentant pas de trouble hyperphagique avaient une balance énergétique négative dans la condition exercice par rapport à la condition contrôle ; les femmes présentant des troubles hyperphagiques ne bénéficiaient pas du déficit énergétique engendré par l'activité physique (Emery et al., 2016). Des adaptations spécifiques devraient donc être mises en place dans la prescription d'activité physique dans cette population.

Des études ont mis en avant certains caractères psychologiques qui seraient associés à la perte de contrôle et aux frénésies alimentaires. Tout d'abord, il apparait que les personnes ayant de mauvaises stratégies de régulation des émotions sont à rique d'hyperphagie. Ainsi, l'affectivité augmenterait la consommation alimentaire et rendrait le contrôle du poids plus difficile. Dans la littérature, le terme « d'alimentation émotionnelle » est employé pour désigner la régulation de la PA selon les ressentis émotionnels. Ainsi, aussi bien chez l'adulte que chez l'enfant, il apparait que les émotions (souvent négatives, comme le stress, l'anxiété ou encore la colère) peuvent augmenter la PA, et cela indépendamment des besoins intrinsèques en énergie (Ranzenhofer et al., 2013). L'aliment est considéré comme un réconfort qui vient apaiser les troubles émotionnels. On retrouve également des associations significatives entre la personnalité affective et la présence de symptôme d'addiction alimentaire. Dans l'étude de Schneider at al. (Schneider et al., 2009) 65 participants en surpoids ou en situation d'obésité ont réalisé deux sessions expérimentales dans un ordre randomisé : une condition contrôle et une condition exercice qui étaient suivies d'un buffet *ad libitum*. De plus, avant et après chaque session expérimentale, les émotions des participants étaient relevées à l'aide du questionnaire « Profile of Mood States ». Les résultats indiquent que lorsque l'exercice est perçu comme une condition stressante, les participants augmentent leur PA par rapport à la condition contrôle, ce qui n'est pas le cas lorsque l'exercice n'engendre pas de détérioration émotionnelle (Schneider et al., 2009). Ces travaux méritent un grand intérêt puisqu'ils soulignent l'importance de prendre en considération, lors de la prescription de l'activité physique, son effet sur les émotions au regard des conséquences que cela entraine sur les comportements alimentaires chez des sujets en situation d'obésité.

Par ailleurs, les troubles hyperphagiques ont été associés à une sensibilité accrue aux stimuli alimentaires. Chez l'adulte, il est en effet aujourd'hui bien établi que certains individus sont plus sensibles à la vue ou à l'odeur des aliments, et qu'il est plus difficile pour ces personnes d'y résister (Hou et al., 2011). La théorie de l'externalité alimentaire, avancée par Schachter et al. dès 1968, décrit des mangeurs dits « externes » pour qui la régulation de la PA ne s'effectue pas en fonction de signaux internes tels que la faim ou le besoin énergétique, mais en fonction de signaux externes comme la simple vue d'un aliment, par exemple (Schachter, 1968). Pour ces mangeurs, il est difficile de résister à la tentation et on retrouve dans la littérature de fortes associations entre le niveau d'externalité et de désinhibition alimentaire. Pour la première fois en 2016, une étude a aussi démontré cette association entre externalité alimentaire et hyperphagie chez l'adolescent (Schmidt et al., 2016). L'étude comptait 25 adolescents âgés de 12 à 20 ans présentant des troubles d'hyperphagie et 25 adolescents « contrôles » (appariés pour le sexe, l'âge, l'IMC et le statut socio-économique). L'activité oculaire de ces derniers a été analysée via la méthode d' « eyes-tracking » au cours d'une tâche de recherche visuelle sur ordinateur. Les résultats indiquent que le groupe avec hyperphagie montre, d'une part un biais de détection pour les cibles alimentaires supérieur au groupe contrôle, et d'autre part un temps de regard plus important pour ces stimuli, ce qui reflète leur plus haut niveau d'externalité alimentaire par rapport au groupe contrôle (Schmidt et al., 2016).

Finalement, il semblerait que la sensibilité accrue aux signaux alimentaires et les phases d'hyperphagies soient la résultante d'un état de privation chronique. Le modèle actuel de la beauté est en faveur de corps filiformes et la pression socio-culturelle pour être mince se fait sentir chez les adolescents, en particulier chez ceux qui sont en surpoids ou en situation d'obésité. Cette pression tend à augmenter la fréquence des régimes hypocaloriques amaigrissants, totalement inadaptés (Caqueo-Urízar et al., 2011). La restriction cognitive est un état d'esprit de privation envers la nourriture pour limiter tant les quantités ingérées que certains macronutriments (les lipides ou les sucres le plus souvent). C'est un trouble psychopathologique qui explique, dans la plupart des cas, les échecs lors de régimes amaigrissants. En effet, les personnes en état de privation alimentaire ont tendance à se focaliser sur la nourriture et, comme précédemment évoqué, y résister devient plus difficile. Par ailleurs, l'internalisation des normes promues par les médias renforce la mauvaise estime de soi et les émotions négatives liées au corps et à l'apparence. Or comme détaillé ci-dessus, les émotions négatives peuvent être responsables de l'initiation de la PA, indépendamment des besoins en énergie. La restriction alimentaire est souvent associée à l'hyperphagie en raison d'un mécanisme de « désinhibition » qui se met en place dès le moindre écart à la règle observée. En effet, les personnes qui sont dans une restriction très stricte vont abandonner le contrôle et basculer dans la désinhibition à partir du moment où elles auront désobéi à leurs interdits. C'est ainsi qu'on observe des phases de restriction-désinhibition (Westenhoefer, 1991). Pour conclure, ces caractéristiques psychologiques (émotionnalité, externalité, restriction, désinhibition) s'influencent mutuellement et sont précurseurs de troubles hyperphagiques dont il est important de tenir compte dans la prescription de l'activité physique (Snoek et al., 2013).

L'étude de Sim et al. en 2018 indique que l'exercice physique peut avoir un effet « contre-productif » chez les individus présentant un haut niveau de restriction alimentaire (Sim, et al., 2018). Dans cette étude, 21 hommes en surpoids devaient prendre part à deux sessions randomisées : un buffet *ad libitum* suivi d'un exercice physique et une session contrôle constituée uniquement d'un buffet *ad libitum.* Les participants devaient renseigner, lors d'une visite préalable, leur profil psychologique vis-à-vis de l'alimentation à l'aide du Dutch Eating Behavior Questionnaire. Les résultats montrent que chez les individus « non-restreints » la prise alimentaire n'est pas significativement différente dans les deux conditions. En revanche, les individus restreints (score moyen de restriction alimentaire supérieur ou égale à 3) mangent plus au buffet *ad libitum* précédant l'exercice, par rapport à la session contrôle (voir figure 11, Sim et al., 2018).

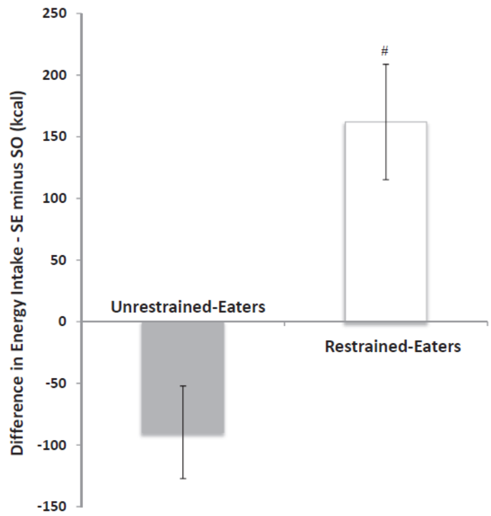


Figure 11 : Delta de la prise alimentaire entre la condition avec exercice et la condition contrôle d'après Sim et al. 2018 **(SE = *ad libitum* Snack + Exercice ; SO = *ad libitum* Snack Only)**

Ainsi, comme précédemment décrit dans la littérature, la restriction cognitive n'est pas forcément un profil psychologique favorable à la perte de poids. En effet, il semblerait que les individus « restreints » aient tendance à fonctionner selon le mode de la compensation : ils mettent en place des comportements qui leur « autorisent » des écarts alimentaires qui, *in fine,* ne permettent pas la perte de poids. Ainsi, dans l'étude de Sim et al. les individus restreints mangent plus lors du repas qui précède l'exercice, car ils auraient anticipé la dépense que ce dernier va engendrer. Ils ne bénéficient donc pas de la perte énergétique induite par l'exercice sur le contrôle de la balance énergétique.

Les résultats de l'étude de McCaig et al. vont dans le même sens, confirmant que lorsque les participants pensent avoir eu une DE importante (par une session d'exercice physique) ils mangent davantage, comparativement à lorsque leur DE leur semble moins importante (McCaig et al., 2016). Dans cette étude, les participants devaient réaliser une session d'exercice à intensité modérée sur ergocycle jusqu'à atteindre la dépense énergétique cible de 120 kcal. Cependant, des informations différentes concernant la dépense énergétique étaient communiquée aux participants, selon le groupe expérimental auquel ils avaient été affectés : 50 ou 265 kcal. Ainsi, à trois reprises les expériementateurs ont indiqué aux participants la cible énergétique qu'ils visaient (soit 50 kcal, soit 265 kcal) (1) avant qu'ils réalisent l'exercice, (2) au moment où la cible était atteinte (3) après l'exercice. Suite à cela un buffet *ad libitum* était proposé aux participants. Les résultats indiquent que la condition 265 kcal entraine une augmentation de la PA *ad libitum* par rapport à la condition 50 kcal, principalement médiée par une augmentation de la consommation de cookies. De manière intéressante, les auteurs montrent que le niveau de restriction cognitive modifie les réponses nutritionnelles à l'exercice physique. Toutefois, en contradition avec l'étude de Sim et al., les résultats indiquent que les individus les moins restreints sont ceux qui augmentent le plus leur PA dans la condition 265 kcal, par rapport aux plus restreints. Ainsi chez les individus peu restreints, il y a un écart de 128 kcal entre les deux conditions (+128 kcal dans la condition 265 kcal) tandis que chez les individus fortement restreints il n'y a pas de différence significative de la consommation entre les deux conditions (+32 kcal dans la condition 265 kcal) (McCaig et al., 2016).

Il semble, au regard de la littérature présentée ci-dessus, que mieux comprendre les mécanismes cognitifs qui interagissent avec les réponses nutritionnelles à l'exercice s'avère essentiel pour identifier les profils d'individus qui vont augmenter leur PA suite à l'exercice, à l'opposé de ceux qui vont la diminuer. Si un certain nombre d'études sont disponibles chez l'adulte, peu se sont intéressées à cette question chez l'adolescent en surpoids. L'implication des voies neurocognitives dans les adaptations nutritionnelles post-exercice a d'ailleurs récemment été ajoutéerésult au modèle initial proposé par Blundell, dans une revue questionnant spécifiquement les interactions entre exercice et PA chez l'adolescent en situation d'obésité (figure 12, Thivel et al. 2019). Les adaptations nutritionnelles à l'exercice et l'activité physique dans cette population se doivent d'être investiguées et les mécanismes neurocognitifs sous jacents explorés. Cela conditionne la réussite d'un programme perte de poids, ainsi que la santé des adolescents en situation d'obésité, et celle des futurs adultes qu'ils seront.

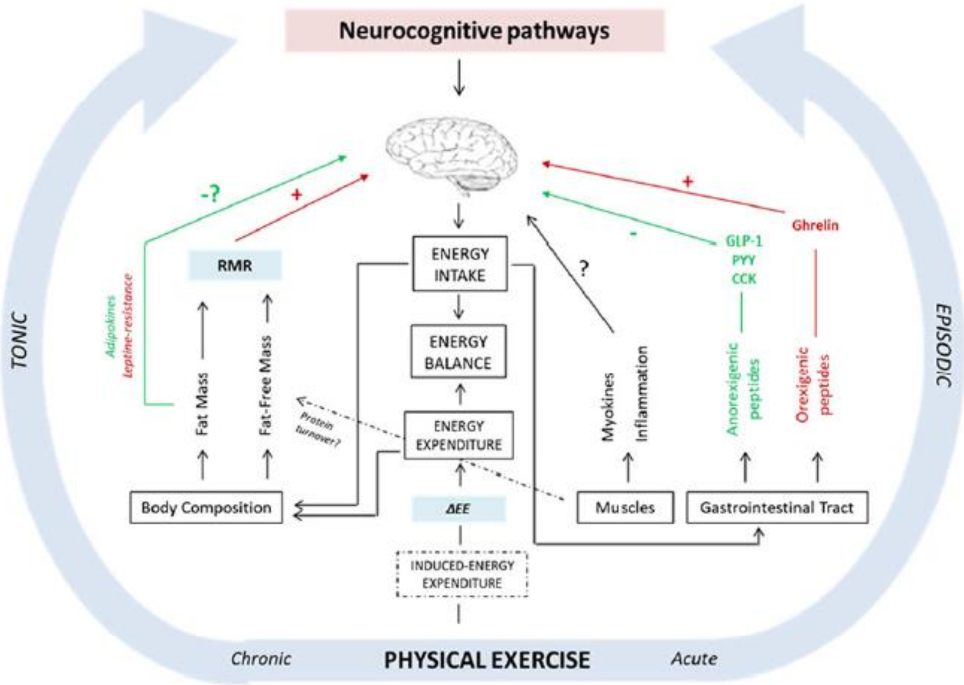


Figure 12 : Mécanismes physiologiques et neurocognitifs impliqués dans la réponse nutritionnelle post-exercice d'après Thivel et al. 2019

DEUXIÈME PARTIE :

CONTRIBUTIONS PERSONNELLES

Objectifs

La revue de la littérature détaillée précédemment nous a amenés à faire plusieurs constats. Premièrement, malgré la hausse de l'obésité pédiatrique et du besoin croissant de développer des prises en charge efficaces pour lutter contre cette maladie, nous ne pouvons toujours pas aujourd'hui conclure quant à l'effet de l'activité physique chronique sur les comportements alimentaires des jeunes en situation d'obésité. Toutefois, identifier, comprendre, et modifier si besoin ces réponses nutritionnelles pourrait permettre d'optimiser les prises en charge et d'obtenir de meilleurs résultats. Si quelques études sont disponibles à ce jour (pour revue voir Schwartz et al., 2017), elles présentent pourtant d'importantes limitations méthodologiques. Il est donc nécessaire de questionner ces adaptations nutritionnelles avec des outils objectifs et des designs spécifiques.

Par ailleurs, au vu de la popularité grandissante du travail intermittent de haute intensité, en raison des intérêts qu'il présente pour la prise en charge et le traitement de l'obésité, investiguer les adaptations nutritionnelles générées par cette modalité de pratique, en comparaison avec les prises en charge dites « classiques » s'avère essentiel. En effet, à ce jour aucune étude n'a questionné l'effet de cette modalité de pratique sur la prise alimentaire chez l'adolescent en situation d'obésité, tant en aigu qu'en chronique. De plus, investiguer l'effet de différentes modalités de pratique permettrait de comprendre si les résultats observés sont variables en fonction de la nature du programme d'activité physique.

D'autre part, il semblerait que l'effet de l'exercice aigu sur la prise alimentaire soit dépendant du statut-pondéral : il induit une diminution de la prise alimentaire chez les adolescents en situation d'obésité mais pas chez les adolescents normo-pondérés. Ce constat soulève la question d'un continuum existant entre les sujets minces et en situation d'obésité et celle de l'effet du degré d'obésité sur la réponse nutritionnelle à l'exercice. Cette question se doit d'être investiguée.

Enfin, si la revue de la littérature nous renseigne sur les mécanismes potentiels impliqués dans les adaptations nutritionnelles à l'exercice, peu d'études interrogeant les paramètres cognitifs existent à ce jour chez l'adolescent en situation d'obésité. Néanmoins, au regard des connaissances actuelles, l'implication du système cognitif dans les réponses nutritionnelles à l'exercice semble évidente. En effet, si actuellement aucune étude n'a questionné le rôle du profil psychologique vis-à-vis de l'alimentation sur les adaptations nutritionnelles post-exercice chez les jeunes en situation d'obésité, cela semble pourtant être une piste pertinente pour la différenciation des individus « répondeurs » et « non-répondeurs ». En outre, si l'environnement actuel dit « obésogène » favorise la régulation hédonique des comportements alimentaires, étudier le système de la récompense et plus précisément, son implication dans la réponse nutritionnelle post-exercice semble primordial.

Face à ces constats, l'objectif principal de ce travail sera de questionner les réponses nutritionnelles à l'exercice physique chez l'adolescent en situation d'obésité, à travers les 4 études suivantes :

- La première étude visera à ***explorer les réponses nutritionnelles (prise alimentaire, répartition macro-nutritive, sensations d'appétit) suite à 10 mois de prise en charge multidisciplinaire de perte de poids chez des adolescents obèses (ÉTUDE 1)***, en utilisant une mesure objective de la prise alimentaire. Par ailleurs, dans cette première étude nous questionnerons le rôle du profil psychologique des adolescents vis-à-vis de l'alimentation (alimentation émotionnelle, externalité et restriction cognitive) dans ces adaptations nutritionnelles et dans la réussite de la prise en charge.

- La deuxième étude visera à ***comparer l'effet de deux programmes multidisciplinaires de perte de poids (de 4 mois) combinant des modalités d'exercices différentes sur les comportements alimentaires (ÉTUDE 2).*** L'efficacité de la prise en charge et les adaptations nutritionnelles seront comparées en réponse à d'une part un programme à haute intensité par intervalles et d'autre part à un programme réalisé à intensité modérée en continu. Comme dans l'étude précédente, une méthode objective sera utilisée pour explorer les adaptations nutritionnelles. Enfin, le rôle du profil psychologique vis-à-vis de l'alimentation sera également exploré dans la réussite de la prise en charge et dans les adaptations nutritionnelles.

- La troisième étude questionnera pour la première fois ***l'effet d'un exercice aigu à haute intensité par intervalle sur les adaptations nutritionnelles chez l'adolescent en situation d'obésité (ÉTUDE 3).*** De plus, pour la première fois également, nous étudierons l'effet de l'exercice sur le système de la récompense dans cette population. Enfin, nous questionnerons le rôle du degré d'obésité dans les réponses nutritionnelles observées.

- Finalement, la quatrième étude s'intéressera aux ***modifications du système de la récompense au cours d'une prise en charge multidisciplinaire de 10 mois et à son association avec les réponses nutritionnelles observées (prise alimentaire, répartition macro-nutritive, sensations d'appétit) chez l'adolescent en situation d'obésité (ÉTUDE 4).***

Les objectifs des études sont résumés sur la figure ci-dessous.

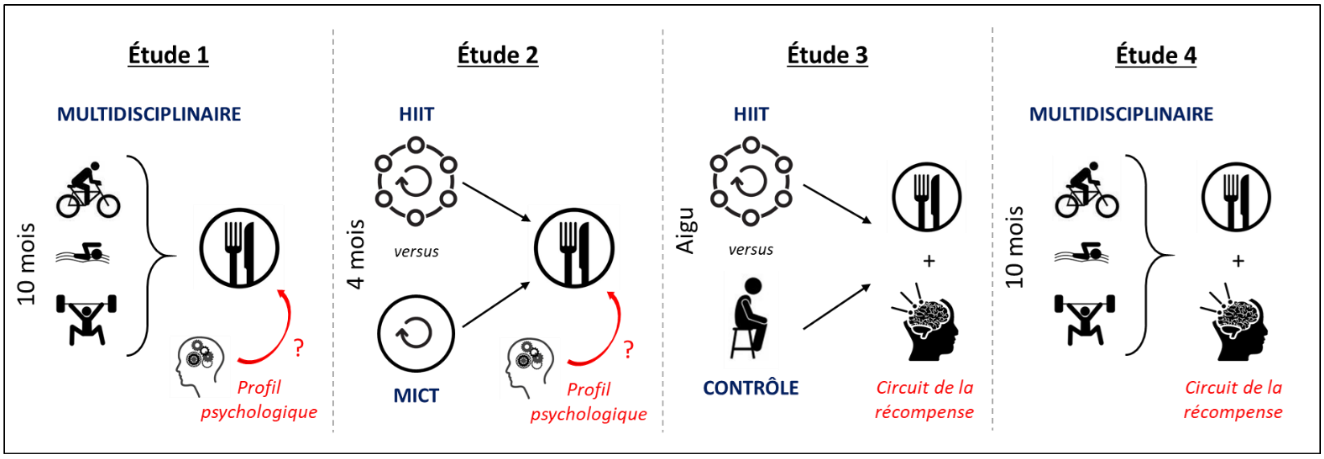


Figure 13 : Objectifs de la thèse

ÉTUDE I :

Effet de 10 mois de prise en charge multidisciplinaire sur la prise alimentaire et son contrôle chez l'adolescent en situation d'obésité : impact du profil psychologique vis-à-vis de l'alimentation.

Cognitive restriction accentuates the increased energy intake response to a 10-month multidisciplinary weight loss program in adolescents with obesity

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Cognitive restriction accentuates the increased energy intake response to a 10-month multidisciplinary weight loss program in adolescents with obesity

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Abstract

Background. Multidisciplinary interventions have shown some merits in weight reduction strategies in youth; however, their impact on subsequent daily energy intake remains largely unknown. The aim of the present study was to evaluate the nutritional responses to a 10-month multidisciplinary intervention among adolescents with obesity, in relation to their eating behavior characteristics.

Methods. Thirty-five adolescents (mean age: 13.4 ± 1.2 years) with obesity took part in a 10-month residential multidisciplinary weight loss program. Anthropometric measurements, body composition (dual-energy X-ray absorptiometry), 24-hour *ad libitum* energy intake (weighted), eating behaviors (Dutch Eating Behavior Questionnaire) and appetite sensations (Visual Analogue Scales) were assessed on three occasions: at their arrival in the institution (T0), after 5 months (T1), and at the end of the 10-month program (T2).

Results. The mean weight loss reached 11% of the adolescents' initial body weight, with an important inter-individual variability (-25% to +3% of their initial body weight). Results revealed sex differences changes, with boys showing a higher decrease in fat mass percent and increase in fat-free mass compared with girls. Weight loss was accompanied by a significant decrease in emotional (-8.3%, $p<0.05$) and external (-14.8%, $p<0.001$) eating scores and a significant increase in 24-hour *ad libitum* energy intake (+246 kcal, $p<0.001$). The observed subsequent increased 24-hour *ad libitum* energy intake at T2

compared to T0 was significantly higher in cognitively restrained eaters (+492 kcal) compared to unrestrained eaters (+115 kcal, $p = 0.015$). Dietary restraint score at baseline was inversely correlated with the percentage of weight loss ($r = -0.44$, $p = 0.010$).

Conclusion. A 10-month multidisciplinary weight loss intervention induced an increase in 24-hour *ad libitum* energy intake compared to baseline, especially in cognitively restrained eaters. Moreover, initially cognitively restrained eaters tended to lose less body weight compared to unrestrained ones. These findings suggest that cognitive restriction may be a useful eating behavior characteristic to consider as a screening tool for identifying adverse responders to weight loss interventions in youth.

Key words: Weight Loss, Multidisciplinary Intervention, Energy Intake, Dietary Profile, Restrained Eaters, Pediatric Obesity

Introduction

Childhood obesity is a public health concern with one out of five children having obesity in Europe [1]. Since obese adolescents have an 80% increased risk of becoming obese adults [2] and developing associated metabolic disorders that might increase their morbidity and reduce their life expectancy [3], developing effective strategies to address childhood obesity remains a priority.

The social pressure to be thin has adverse effects by promoting body dissatisfaction, negative affects and disrupted eating attitudes and behaviors [4], and concerns for dieting and cognitive restriction can start very early in children [5], [6]. In particular, young overweight adolescents are reporting higher sociocultural and familial pressures to reach an ideal body weight. Although some cross-sectional studies highlight that restrained eating is positively associated with body weight [7]–[9], it remains difficult to determine whether restrained eating is a cause or a consequence to overweight [10], [11]. Several studies have been conducted in adults, providing evidence for both increased [12]–[14] or decreased body weight [15] among dietary restrained individuals; however, this remains largely unexplored among children and adolescents. Studies are particularly needed regarding the potential effect of eating behavior traits, especially dietary restraint, on the success and efficacy of anti-obesity interventions among adolescents.

“Restrained eating” (i.e., cognitive effort to restrict energy density and food consumption [16]) has been associated with potential risks for overeating through its association with disinhibition (i.e. the tendency to overeat in response to different stimuli [17]). Cognitive restriction ignores appetite sensations and internal needs but refers to external rules and diet restrictions to regulate energy intake. Cognitive restriction could therefore appears as an ally to maintain (or lose) weight. Besides, when coupled with low disinhibition rate, cognitive restriction has been associated with beneficial dietary patterns and a successful weight management [18], [19]. However, many studies highlighted the link between cognitive restriction and binge eating [12]–[14], which could explain why cognitive restriction is associated, on the long term, with weight gain.

Physical activity has recently been described as a good strategy for decreasing eating disorders, food reward and energy intake in adults and obese adolescents [20], [21]. Recently, Martin-Gracia et al. [22] found that a 3-month vigorous physical activity intervention decreased emotional eating in overweight boys and girls. In their systematic review, Schwartz et al. [21] concluded that physical activity interventions helped to decrease daily energy intake in adolescents with obesity. Such results suggest that the effect of physical activity interventions on overall health, body weight and body composition might be in part mediated by modifications in eating behaviors in youth with obesity. However, most studies relied on self-reported dietary intake, which, as indicated by previous work, is a major limitation for the interpretation of findings [21]. Moreover, as obesity is a multifactorial disease, it appears essential to combine different disciplines to favor long-term improvements.

Multidisciplinary interventions combining physical activity, nutritional guidelines and psychological support are recommended among youth with obesity [23]. Such interventions have been shown effective (at least in the short term), leading to significant improvements in body weight and body composition [24], physical fitness [24], cardio-metabolic profile [25], and health-related quality of life [26] among others. However, they have also been found to suffer from an important inter-individual variability in the response to the programs among adolescents [27]. It thus seems important to better understand the main characteristics that can explain this variability in order to better individualize these programs. Eating behavior appears as one important candidate whose implication in the success of weight loss programs has to be explored [28], [29].

Given the clinical importance of identifying the individual determinants that could help improving our long-term obesity reduction strategies, this study aimed to explore the effect of a 10-month multidisciplinary intervention on body composition, energy intake and eating behaviors in adolescents with obesity, questioning whether certain eating behavior traits of adolescents could be associated with the success of the intervention. This information is important because it could help to better screen for good and adverse responders to a weight loss program, and may provide additional tools to health care providers wishing to reduce the inter-individual variability generally observed for any given weight loss intervention.

Methods

Participants

A total of 35 adolescents (mean age: 13.4 ± 1.2 years) with obesity as defined by Cole et al. [30] (mean BMI z-score: 2.2 ± 0.4; BMI percentile: 98.0 ± 2.7) were enrolled in this study (12 boys and 23 girls) through local pediatric consultations. Convenience sampling was used in this study. To be included, the adolescents had to: i) be aged between 11 and 15 years; ii) present a BMI equal or above the 95th percentile for their gender and age [30]; iii) be free of any medication that could interact with the protocol (e.g., thyroid medication, stimulant medication, medication for diabetes); iv) present no contraindication to physical activity; and v) take part in less than 2 hours of physical activity per week (according to the International Physical Activity Questionnaire – IPAQ). All the adolescents and their legal representative received information sheets and signed up consent forms as requested by the ethical authorities.

Protocol design

After a medical inclusion realized by a pediatrician to ensure their ability to complete the study, the adolescents were enrolled in a 10-month residential multidisciplinary weight loss program in a local Pediatric Obesity Center (Tza Nou, La Bourboule, France). Maturation status was assessed by the physician using the Tanner stages during the first medical visit. Anthropometric measurements, body composition (dual-energy X-ray absorptiometry), resting metabolic rate (indirect calorimetry), daily energy intake (*ad libitum* buffet meals), eating behavior traits (Dutch Eating Behavior Questionnaire) and appetite sensations (visual analogue scales) were assessed before (T0), after 5 months (T1), and at the end of the 10-month program (T2). This study was conducted in accordance with the Helsinki declaration and received an ethical agreement from official authorities (CPP Sud Est VI: 2015-33; Clinical Trial NCT02626273).

Measurements

The following measurements have been performed on three different occasions (baseline, intermediaries and at the end of the 10-month intervention).

Anthropometric characteristics and body composition

Body weight and height were recorded to the nearest 0.1 kg and 0.5 cm, respectively, while wearing light clothes and bare-footed, using respectively a digital scale and a standard wall-mounted stadiometer. BMI was calculated as weight (kg) divided by height squared (m^2). Afterwards, BMI was reported in the sex and age dependent French reference curves to get the BMI percentile. Fat mass (FM) and fat-free mass (FFM) were assessed, under fasted state, by dual-energy X-ray absorptiometry (DXA) following standardized procedures (QDR4500A scanner, Hologic, Waltham, MA, USA).

Eating behavior traits

Eating behavior traits were assessed using the Dutch Eating Behavior Questionnaire (DEBQ) [31]. Three domains were evaluated: restrained eating (individuals' efforts to limit their food intake to control body weight or to promote weight loss; 10 items), emotional eating (excessive eating in response to negative moods; 13 items) and external eating (eating in response to food-related stimuli, regardless of the internal state of hunger or satiety; 10 items). Participants filled the 33 items in a six-point Likert scale (never (1), seldom (2), sometimes (3), often (4), very often (5) and not relevant (0)). Their answers were coded following the instructions given by Lluch et al. [32]. Means for each domain were calculated, with higher scores indicating greater endorsement of the eating behavior. Scores equal to or above three were used to categorize adolescents as restrained, emotional and/or external eaters [33]. This questionnaire has been previously validated in its French version [32].

Ad libitum energy intake

Daily *ad libitum* energy intake was assessed during three single test days performed at baseline (T0), in the middle (T1) and at the end of the program (T2). At 08:00, after an overnight fast, the adolescents consumed a standardized calibrated breakfast respecting the recommendations for their age (≈500 kcal) [34]. Lunch and dinner meals were served *ad libitum* using a buffet-type meal. The content of the buffets was determined based on the adolescent's food preferences and eating habits. Top rated items as well as disliked ones and items liked but not usually consumed were excluded to avoid over-, under- and occasional consumption. At lunch, the menu was composed of beef steaks, pasta, mustard, cheese, yogurt, apple sauce, fruits and bread. Dinner menu was composed of ham/turkey, beans, mashed potatoes, cheese, yogurt, apple sauce, fruits and bread. Food items were presented in abundance and accompanied with tap water only. Adolescents made their choices and composed their trays individually before joining their habitual table (5 adolescents per table). Adolescents were told to eat until feeling comfortably satiated and had access to extra food if wanted. Food intake was weighted by the experimenters and the macro nutritive distribution (proportion of fat, carbohydrate and protein) as well as the total energy consumption in kcal were calculated using the software Bilnut 4.0. Total daily energy intake was calculated by summing up breakfast, lunch and dinner meals. This methodology has been previously validated and published [35]. Between the two *ad libitum* test meals, the adolescents were requested not to engage in any moderate to vigorous physical activity and mainly performed sedentary activities such as reading, homework, or board games.

Subjective appetite sensations

Appetite sensations were collected throughout the day using visual analogue scales (150 mm scales). Adolescents had to report their hunger, fullness, desire to eat and prospective food consumption at six regulated times: before and right after the breakfast, lunch, and dinner. The questions were i) "How hungry do you feel?", ii) "How full do you feel?", iii) "Would you like to eat something?", iv) "How much do you think you can eat?" (adolescents were asked to respond on a scale from "not at all" to "a lot"). This method has been previously validated [36].

Resting metabolic rate

Resting metabolic rate (RMR) was measured in the morning, under fasted state, using indirect calorimetry ($K4b^2$, Cosmed, Rome, Italy). Before each test, gas analysis was calibrated in accordance with the manufacturer's recommendations. Participants extended in a supine position in a thermoneutral environment (22–25°C room temperature) for 45 min before starting the measurements. After achieving a steady state, O_2 consumption and CO_2 production standardized for temperature, barometric pressure and humidity was recorded at 1 min intervals for 20–45 min and averaged over the whole measurement period. Resting metabolic rate (in kcal/day) and respiratory quotient (ratio of CO_2/O_2) were thereafter calculated.

Multidisciplinary weight loss program

The 10-month residential multidisciplinary weight loss program combined physical activity, nutritional education and psychological support. The physical activity intervention was composed of four 60-minute physical activity sessions per week including aerobic training, strength training, aquatic activities and leisure-time activities (e.g. soccer). Concomitantly, the adolescents attended 2 hours of physical education per week at school. The adolescents also attended nutritional education classes twice a month led by a dietician and received psychological support through individualized consultations with a professional once a month. During the intervention, the adolescents were submitted to a normo-caloric diet based on their age and sex recommendations [37].

Statistical analysis

Statistical analyses were performed using Statview (version 4 for Windows) and Stata software, Version 13 (StataCorp, College Station, TX, US). All tests were two-sided, with a Type I error set at 0.05. Continuous data was expressed as mean ± standard deviation (SD) or median [interquartile range] according to statistical distribution. The assumption of normality was assessed by using the Kolmogorov-Smirnov test. Random-effects models for repeated data were performed to study the evolution between T0, T1 and T2 for weight, body composition, RMR, eating behaviors, *ad libitum* energy intake and macronutrient consumption among boys and girls. For appetite sensations, area under the curves (AUC) based on the trapezoid methods was also analyzed. Then, the following fixed effects were evaluate: *time*, *gender* and *time x gender* interaction, taking into account between and within patient variability (subject as random-effect). When appropriate, a Šidák's post-hoc test for multiple two by two comparisons was applied. The normality of residuals from these models was studied using the Shapiro-Wilk test. When appropriate, a logarithmic transformation was proposed to achieve the normality of dependent outcome.

Concerning non-repeated measures, quantitative variables were compared between groups by means of analysis of variance (ANOVA) or Kruskal-Wallis test when the assumptions of ANOVA were not met (normality and homoscedasticity analyzed using the Bartlett test). These analyses were conducted to compare (i) baseline parameters (e.g., weight, body composition) and their variation at the end of the 10-month intervention between restrained and non-restrained eaters, emotional and non-emotional eaters, and external and non-external eaters and (ii) eating behavior scores between adolescents who achieved more than 10% weight loss *versus* those who lost less than 10% of their initial body weight and (iii) energy intake between the four different trajectories of cognitive restraint during the 10-month weight loss intervention (i.e., restrained adolescents staying restrained; restrained adolescents becoming non-restrained; non-restrained adolescents staying non-restrained; and non-restrained adolescents becoming restrained). As proposed by some statisticians [38], [39] a particular focus will be given to the magnitude of differences, in addition to inferential statistical tests expressed using p-values. The results were expressed using Hedges's effect-sizes and regression coefficients with 95% confidence intervals. Categorical parameters were compared between groups using Chi-squared or Fisher's exact tests, notably to compare restrained and non-restrained responses to the *ad libitum* meal. The relationships between quantitative variables (more precisely between baseline eating behavior scores and weight and body composition variations) were studied estimating correlation coefficients (Pearson or Spearman, according to statistical distribution) applying a correction of type I error (Šidák's).

Results

Participant characteristics

Among the initial 41 children included, 35 completed the 10-month intervention (85% retention). Data analyses were performed on these 35 children. Of the six participants who left the trial, 1 dropped out for family reasons, 3 were excluded for disciplinary reasons, and 2 for school-related reasons. None of the drop outs was related to the study protocol.

Anthropometric and metabolic parameters were not significantly different among boys and girls at baseline. Changes are presented in Table 1. Body weight and BMI decreased significantly through the intervention in the same way for boys and girls. FM percent decreased significantly in both groups with a higher decrease in boys (p for interaction <0.0001). FFM significantly decreased in girls during the intervention whereas it increased in boys (p for interaction <0.0001). Inter-individual body weight, FM and FFM variations among boys and girls are presented in Figure 1. Resting metabolic rate only changed among boys, with a significant increase. Resting respiratory quotient significantly decreased in both groups with no gender effect.

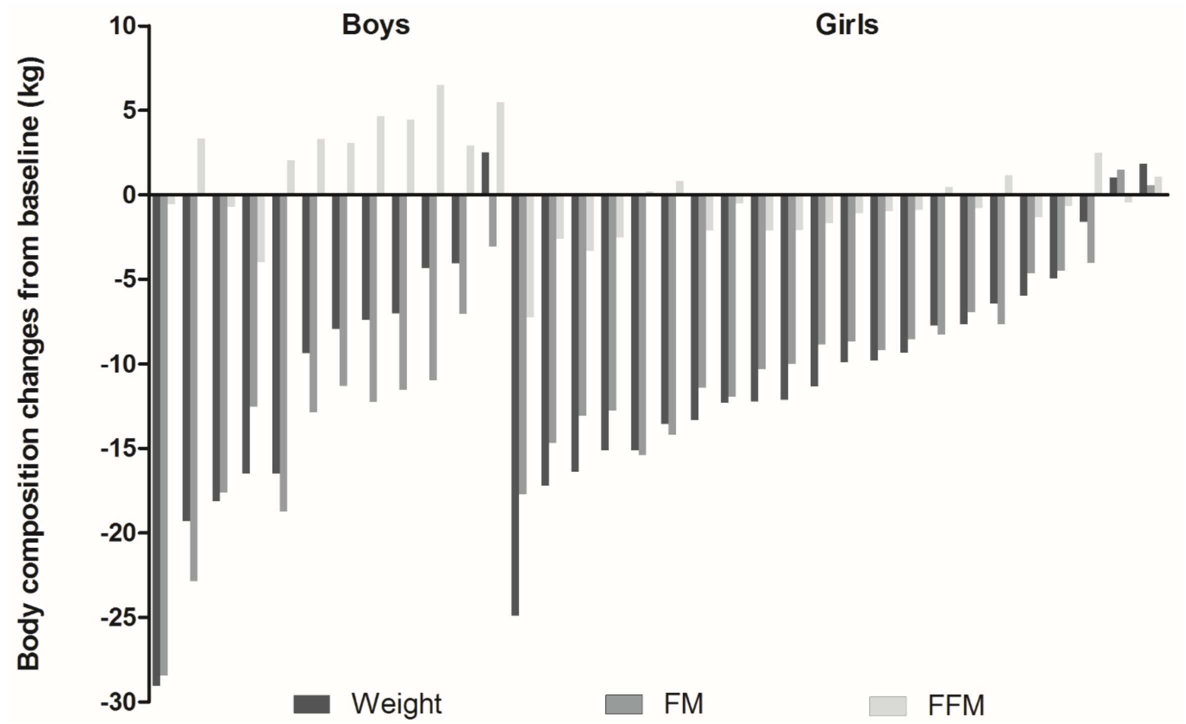

Figure 1. Inter-individual differences in weight, fat mass (FM) and fat-free mass (FFM) variations in response to a 10-month multidisciplinary weight loss program among boys and girls.

Table 1. Anthropometric and metabolic changes among boys and girls throughout the 10-month weight loss multidisciplinary program.

		T0 Mean (SD)	T1 Mean (SD)	T2 Mean (SD)	Time effect	Hedges g	Sex effect	Time x Sex	Regression coefficient
Weight (kg)	Boys n=12	90.8 (18.2)	83.5 (13.8)***	79.4 (12.5)$^{***\#}$	<0.0001	0.69 [0.20, 1.16]	NS	NS	1.25 [-2.30, 4.81]
	Girls n=22	87.8 (16.7)	80.4 (14.8)***	77.6 (14.2)$^{***\#\#}$					
BMI (kg/m^2)	Boys n=12	33.6 (4.6)	30.2 (3.8)***	27.9 (3.5)$^{***\#\#\#}$	<0.0001	1.14 [0.63, 1.64]	NS	NS	0.94 [-0.45, 2.33]
	Girls n=22	33.5 (5.1)	29.8 (4.3)***	28.7 (4.1)$^{***\#}$					
FM (%)	Boys n=12	36.9 (5.8)	29.6 (5.0)***	25.4 (6.4)$^{***\#\#\#}$	<0.0001	1.41 [0.89, 1.93]	0.0159	0.0001	4.83 [2.81, 6.85]
	Girls n=22	39.3 (4.7)	33.9 (4.9)^{a***}	32.6 (5.3)$^{b***\#}$					
FFM (kg)	Boys n=12	54.2 (10.6)	56.5 (9.2)**	56.8 (9.2)**	0.0244	-0.03 [-0.50, 0.43]	0.0906	<0.0001	-3.63 [-5.09, -2.17]
	Girls n=22	50.8 (8.3)	50.7 (8.5)	49.7 (7.9)$^{a**\#}$					
RMR (kcal/day)	Boys n=11	2124 (377)	2597 (338)**	2596 (457)**	0.0003	-0.56 [-1.07, -0.05]	0.0042	NS	-327.60 [-645.76, 9.43]
	Girls n=15	1965 (354)	2150 (355)^{c}	2152 (387)^{c}					
RQ (VCO_2/VO_2)	Boys n=11	0.90 (0.10)	0.81 (0.04)**	0.80 (0.08)**	0.0001	1.33 [0.77, 1.89]	NS	NS	0.01 [-0.06, 0.08]
	Girls n=15	0.88 (0.04)	0.83 (0.06)	0.81 (0.09)*					

T0: 0 month; T1: 5 months; T2: 10 months; BMI: Body Mass Index; FM: Fat Mass; FFM: Fat-Free Mass; RMR: Resting Metabolic Rate; RQ: Respiratory Quotient; SD: Standard Deviation. a: significantly different between boys and girls with $p<0.05$; b: significantly different between boys and girls with $p<0.01$; c: significantly different between boys and girls with $p<0.001$; *: significantly different with T0 with $p<0.05$; **: significantly different with T0 with $p<0.01$; ***: significantly different with T0 with $p<0.001$; #: significantly different with T1 with $p<0.05$; ##: significantly different with T1 with $p<0.01$; ###: significantly different with T1 with $p<0.001$.

Table 2. Energy intake and macronutrient consumption changes among boys and girls throughout the 10-month weight loss multidisciplinary program.

		T0 Mean (SD)	T1 Mean (SD)	T2 Mean (SD)	Time effect	Hedges g	Sex effect	Time x sex	Regression coefficient
Lunch EI	Boys n=12	1031 (225)	1236 (281)[*]	1256 (222)[**]	0.0020	-0.54 [-1.00, -0.07]	0.0009	0.0770	-141.95 [-305.01, 21.19]
(kcal)	Girls n=23	897 (238)	912 (240)[b]	980 (203)[c]					
Dinner EI	Boys n=12	1036 (324)	940 (253)	1157 (309)[#]	0.0014	-0.40 [-0.87, 0.07]	0.0141	NS	-10.73 [-189.60, 168.14]
(kcal)	Girls n=23	827 (236)[a]	802 (214)[t]	937 (241)[a*#]					
Total EI	Boys n=12	2570 (502)	2679 (420)	2917 (484)[*]	0.0006	-0.53 [-1.10, -0.52]	0.0010	NS	-152.68 [-421.82, 116.47]
(kcal)	Girls n=23	2228 (402)[a]	2218 (357)[b]	2422 (357)[b*#]					
Proteins	Boys n=12	107.1 (30.6)	116.7 (29.9)	131.3 (23.7)[**#]	<0.0001	-1.25 [-1.76, -0.74]	0.0009	NS	12.41 [-4.17, 28.99]
(g)	Girls n=23	80.9 (20.3)[b]	84.8 (16.9)[c]	117.5 (23.2)[***###]					
Lipids	Boys n=12	67.3 (23.3)	76.5 (22.8)	75.4 (27.3)	NS	-0.11 [-0.57, 0.35]	0.0056	NS	-8.52 [-23.85, 6.81]
(g)	Girls n=23	56.7 (18.7)	55.8 (15.4)[b]	56.3 (20.3)[a]					
CHO	Boys n=12	255.8 (54.7)	250.0 (45.2)	298.5 (54.4)[**##]	0.0020	-0.36 [-0.82, 0.11]	0.0083	NS	-32.30 [-68.62, 4.01]
(g)	Girls n=23	223.0 (53.2)	215.1 (55.9)	233.5 (56.2)[b]					
Proteins	Boys n=12	20.6 (2.6)	21.3 (2.7)	22.0 (3.2)	<0.0001	-1.42 [-1.94, -0.90]	NS	0.0031	4.51 [1.89, 7.13]
(%)	Girls n=23	18.8 (2.1)[a]	20.0 (2.2)	24.7 (3.6)[a***###]					
Lipids	Boys n=12	29.1 (4.8)	31.3 (5.3)	27.5 (6.0)[#]	0.0211	0.39 [-0.8, 0.86]	NS	NS	-1.26 [-5.93, 3.40]
(%)	Girls n=23	29.2 (5.4)	29.4 (5.4)	26.3 (7.6)[*#]					
CHO	Boys n=12	50.0 (5.0)	46.4 (5.5)[*]	49.8 (4.0)[#]	0.0627	0.40 [-0.07, 0.87]	NS	NS	-3.42 [-8.00, 1.12]
(%)	Girls n=23	52.1 (6.4)	50.0 (6.0)	48.5 (6.6)[*]					
Restraint	Boys n=12	2.7 (0.8)	2.9 (0.9)	2.6 (0.7)	NS	-0.02 [-0.49, 0.45]	NS	NS	0.06 [-0.48, 0.60]
score	Girls n=20	2.8 (0.8)	2.7 (0.6)	2.8 (0.7)					
External	Boys n=12	3.3 (0.6)	2.9 (0.8)	2.7 (0.8)[*]	<0.0001	0.41 [-0.66, 0.89]	NS	NS	0.00 [-0.47, 0.48]
score	Girls n=20	3.3 (0.9)	2.6 (0.6)[***]	2.7 (0.6)[***]					
Emotional	Boys n=12	2.8 (1.0)	2.5 (0.9)	2.2 (0.7)[*]	0.0187	0.80 [0.30, 1.29]	NS	NS	0.32 [-0.27, 0.92]
score	Girls n=20	2.2 (0.9)	2.3 (1.0)	1.9 (0.9)					

T0: 0 month; T1: 5 months; T2: 10 months; SD: Standard Deviation; CHO: Carbohydrate; NS: Not Significant; a: significantly different between boys and girls with p<0.05; b: significantly different between boys and girls with p<0.01; c: significantly different between boys and girls with p<0.001; *: significantly different with T0 with p<0.05; **: significantly different with T0 with p<0.01; ***: significantly different with T0 with p<0.001; #: significantly different with T1 with p<0.05; ##: significantly different with T1 with p<0.01; ###: significantly different with T1 with p<0.001.

Energy intake, dietary profile and appetite feelings

As shown in Table 2, baseline dinner and whole day energy intake were higher in boys compared to girls. Boys ate more proteins (in grams and percentage). Both boys and girls showed increased *ad libitum* energy intake at the end of the intervention (boys increased energy intake at lunch, dinner and whole day; whereas girls increased their food consumption at dinner and whole day). Both increased the percentage of proteins and decreased the proportion of lipids and carbohydrate. At baseline, boys and girls showed similar restraint, external and emotional eating scores. Throughout the intervention, external eating scores decreased significantly in both groups; emotional eating scores decreased only in boys and restraint eating scores did not changed.

Fasting and daily hunger, satiety, desire to eat and prospective food consumption (assessed with visual analogue scales) were not significantly different between T0 and T2 (supplementary materials).

Relationships between eating behaviors traits, energy intake and body composition

At baseline, significantly lower body weight and FFM were found in external eaters compared to non-external ones (82.6 *vs.* 97.0 kg for body weight, $p<0.01$, hedges's g = 0.92 [0.22, 1.60], and 48.8 *vs.* 56.0 kg for fat-free mass, $p<0.05$, hedges's g = 0.82 [0.13, 1.50]). FM did not differ between external and non-external eaters. Body weight, FFM and FM did not differ between restrained and non-restrained and between emotional and non-emotional eaters.

A significant inverse correlation was observed between the baseline cognitive restraint eating score and the percentage of weight loss ($p<0.01$; $r = -0.44$), with the adolescents who experienced the greatest weight loss at T2 being the less restrained at baseline. No significant correlation was found between baseline restraint eating score and FM and FFM variations. Similarly, the baseline emotional score and baseline external score were not correlated with weight, FM and FFM variations.

The adolescents who lost more than 10% of their initial weight (at T2 compared with baseline) showed a restraint eating score at baseline that was significantly lower than those who lost less than 10% of their initial weight (2.5 *vs.* 3.1, p = 0.014, hedges's g = 0.91 [0.19, 1.63], Figure 2A).

The FFM variation between baseline and T2 was significantly higher in restrained (≈ +2 kg) compared with non-restrained eaters (≈ -0.6 kg) (p = 0.012, hedges's g = 0.98 [0.21, 1.73], Figure 2B). FM was not differently affected between restrained and non-restrained eaters. Emotional and external aspects of eating behavior did not influence differently fat mass or fat-free mass.

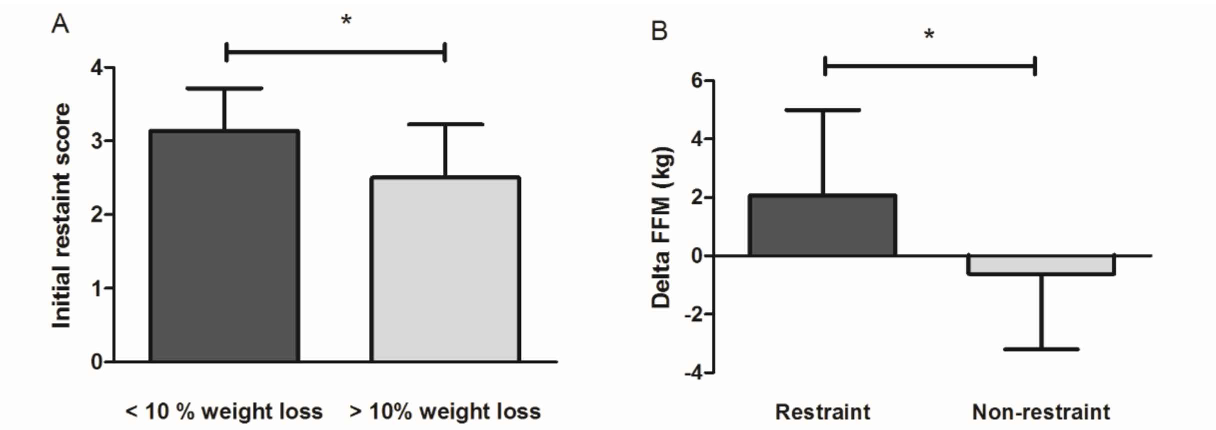

Figure 2A. Percentage of weight loss by initial restraint eating score. **Figure 2B**. Fat-free mass variation depending on the dietary restraint subscale.<10% weight loss n=12; >10% weight loss n=22; Restraint eaters n=10; Non-restraint eaters n=24; *p<0.05.

We did not find any significant correlation between body weight or body composition and energy intake variations. However, the adolescents who were cognitively restrained at T2 (end of the intervention) increased significantly more their *ad libitum* energy intake (+492 kcal in restrained eaters and +115 kcal in non-restrained eaters, p<0.05, hedges's g = 0.90 [0.17, 1.62], Figure 3A). Moreover, 92% of the restrained eaters increased their *ad libitum* energy intake between T0 and T2 compared with only 53% in the non-restrained eaters (p<0.05, Figure 3B).

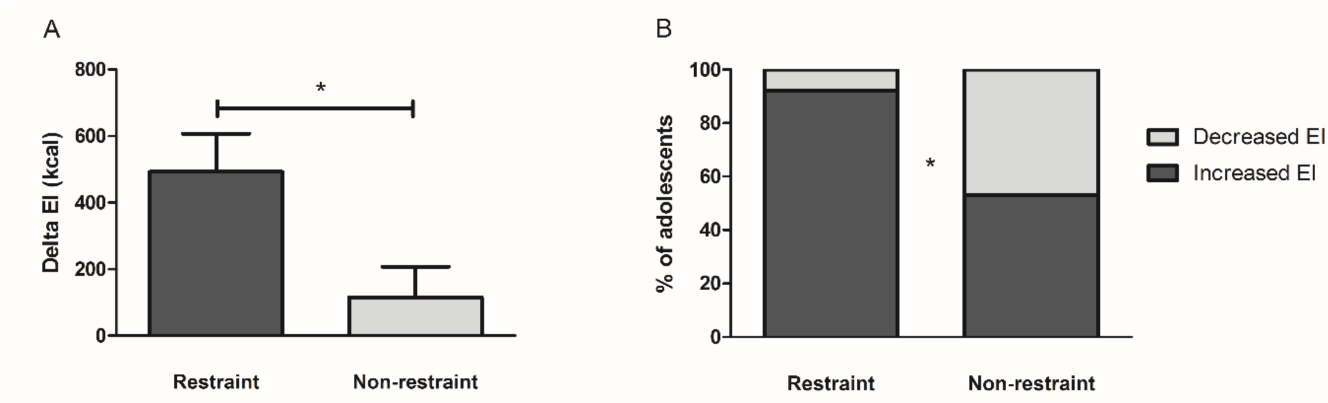

Figure 3A. *Ad libitum* energy intake variation between restrained and non-restrained eaters. **Figure 3B.** Percentage of adolescents increasing or decreasing *ad libitum* energy intake among restrained and non-restrained eaters. Delta EI: Energy Intake at T2-Energy Intake at T0; Restraint eaters n=13; Non-restraint eaters n=19; *: p<0.05

Finally, we classified adolescents depending on their restraint profile modification: i) those who were restrained and became unrestrained (R>>NR); ii) those who were unrestrained and stayed unrestrained (NR>>NR); iii) those who were unrestrained and became restrained (NR>>R); and iv) those who were restrained and stayed restrained (R>>R). *Ad libitum* energy intake during the intervention did not change in the same way between groups (see Fig.4). Time x profile interaction was <0.05. We found a statistically significant difference between NR>>NR and NR>>R (p<0.05; hedges's g = -0.92 [-1.81, -0.02]) and a tendency between R>>NR and NR>>R (p=0.07; hedges's g = 1.01 [-0.08, 2.06]). In other words, adolescents who ate the most at the end of the intervention were those who were unrestrained and became restrained (+558 ± 484 kcal) while the adolescents who were restrained and became unrestrained ate less at T2 compared with baseline (+55 ± 445 kcal).

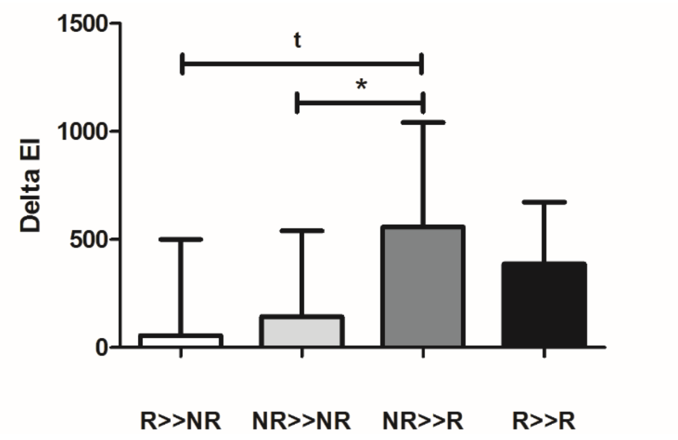

Figure 4. *Ad libitum* energy intake variation depending on the trajectory of cognitive restraint between baseline and the end of the program. Delta EI: Energy Intake at T2-Energy Intake at T0; R: Restraint; NR: Non-restraint; *: p<0.05; t: p=0.07.

Discussion

The aim of this study was to evaluate the nutritional responses (i.e., energy intake, appetite sensations and eating behaviors) to a multidisciplinary weight loss program in adolescents with obesity and to determine whether eating behaviors could be associated with the success of the intervention. We observed that weight loss was accompanied by a modification in the eating behaviors profile, with a significant decrease in emotional (-8.3%, p<0.05) and external (-14.8%, p<0.001) eating scores whereas 24-hour *ad libitum* energy intake increased significantly (+246 kcal, p<0.001). The observed subsequent increased 24-hour *ad libitum* energy intake at T2 compared to T0 was significantly higher in cognitively restrained eaters (+492 kcal) compared to unrestrained eaters (+115 kcal, p = 0.015). Moreover, dietary restraint score at baseline was inversely correlated with the percentage of weight loss (r = -0.44, p = 0.010).

Contrary to the current body of evidence that suggests that multi-component interventions promote decreased daily energy intake in adolescents with obesity [40]–[42], our results showed a significantly increased daily *ad libitum* energy intake (+246 kcal, p<0.001) in response to a 10-month multidisciplinary program. This discrepancy could be explained by the different methodologies used to assess energy intake between the present work and the previous studies (for review see [21]). Indeed, as pointed out in a recent systematic review and meta-analysis, most studies have used self-reported dietary recalls, which remain highly subjective; whereas we used an objective measure of food ingestion (weighted *ad libitum* buffet meals). Self-reported dietary recalls have been shown to provide under-reported food intake, especially among obese adolescents [43], which could partly explain the observed differences between our results and the previous ones.

Although some previous works have shown an increased $PYY_{3\text{-}36}$ concentration concomitantly with a reduction of daily energy intake in response to a 4-month high-intensity training in obese youth [42], or increased anorexigenic factors concentration (AgRP and α-MSH) accompanied by decreased energy intake after a one-year multidisciplinary weight loss intervention in obese adolescents [41] (both studies using self-reported methods to assess energy intake), other studies seem to obtain results that are in line with the increased energy intake observed in the present work. The increased energy ingestion observed in our study could be explained by the up-regulation of appetite hormones such as ghrelin as an adaptive response to energy deficit and weight loss [44], [45]. In their work, Gueugnon et al. [46] found increased fasting ghrelin concentration accompanied by unchanged PYY (total form) after a 9-month multidisciplinary weight reduction program in adolescents with obesity. Their results are reinforced by the increased hunger profile and reduced satiety profile observed by King and colleagues after a 6-week weight loss intervention in a similar population [47]. According to the authors, lowering daily energy intake while increasing energy expenditure through exercise is effective in inducing weight loss but favors sensitive appetite regulation in children with obesity [47]. Although the increased food consumption observed in the present work is in line with these previous results, we did not find any modification in daily appetite sensations (hunger, fullness, prospective food consumption and desire to eat) between baseline and the end of the study, which further supports the hypothesis that physical exercise might have an uncoupled effect on appetite feelings and energy intake in children and adolescents [48]. Moreover, some studies have shown that ingestive behaviors are independent of appetite sensations in some context, where energy intake may be mainly driven by external and environmental factors, but not by hunger or fullness [49].

With regard to macronutrient consumption, our results showed an increase in the relative energy ingested from proteins between T0 and T2 (+4.4%, $p<0.001$), while the energy derived from fat and CHO were found to be decreased (-2.5% and -2.4%, $p<0.05$). Although the available literature indicates decreased intake of each macronutrients (fat, protein and carbohydrates) after chronic multi-component interventions in obese adolescents [21], these studies also used self-reported dietary evaluations that have been shown to provide unsatisfactory results in this population. The shift towards an increase in protein consumption could be related to the observed body composition variations, especially the preservation of fat-free mass.

Multidisciplinary interventions have been described and shown as good strategies for preventing and treating pediatric obesity and its health-related problems [23]–[26]. In support of these previous studies, weight, BMI and fat mass were decreased in response to our 10-month program combining physical activity, nutritional education and psychological support. Although the mean weight loss reached 11% of the adolescents baseline body weight, the figure 1 illustrates an important inter-individual variability with 3 adolescents who did not lose weight and a body weight loss ranging from -25% to -2% of their initial body weight among those who did lose body weight. Interestingly, the figure 1 also reveals sex differences. Indeed, boys were found to have better body composition adaptations than girls, with a higher decrease in fat mass percent and an increase in fat-free mass. This is in accordance with previous works [24] [50] which highlighted sex-specific changes after weight loss. A higher compliance and engagement in the physical activity program among boys compared with girls can be suggested to explain these differences, which is often observed in the general population [51]. As highlighted by Browning and Evans, the preservation of fat-free mass during weight loss appears to be an advantage because of the strong relationship between fat-free mass and resting energy expenditure [52]. The authors specified that the maximization of resting energy expenditure is a desirable outcome in a perspective of long-term weight management. Our results precisely showed a significant increase in resting metabolic rate among boys, which is in line with their increased fat free mass. On the other hand, we found the respiratory quotient significantly decreased among both boys and girls in response to the intervention (indicating a shift in substrate utilization with higher fat and lower carbohydrate oxidation at rest). In line with another trial [53], this result is not surprising as it is well established that exercise (even without inducing negative energy balance) leads to increased fat oxidation [54], [55], which favors weight stability [56].

With regard to eating behavior, previous works have shown that adolescents with obesity scored higher on restrained eating compared to normal-weight ones [11], [57]. In our study, we did not find initial weight or body composition differences between restrained and non-restrained eaters, which is not in line with the literature but could be explained by the high degree of obesity of our sample. Indeed, while most of the studies have been conducted so far among overweight and obese youth, our sample was composed of severely obese adolescents only. Similarly, at the beginning of the program, emotional and non-emotional eaters did not differ in weight, fat mass and fat-free mass. Yet, unexpected results were found concerning the external eating score. Indeed, contradictory to the theory of external eating, we found lower body weight in external eaters compared to non-external ones (respectively 82.6 vs. 97.0 kg body weight, $p<0.01$). This result has already been found in previous studies [10], [11], [57] with some authors suggesting a high influence of parents on overweight children, trying to regulate their food intake and food choices, reducing then their exposure to external food stimuli and making them less vulnerable to external stimuli.

As previously introduced, benefits of multidisciplinary interventions may be explained, among other mechanisms, by a modification of eating patterns and dietary profiles. Accordingly, our results indicate a decrease in emotional (among boys) and external (among boys and girls) eating scores (assessed by the DEBQ) after the 10-month residential multidisciplinary weight loss program. In other words, our intervention was effective in decreasing overeating in response to emotional and external situations, showing that adolescents better coped with emotional and external cues and referred more to internal cues. In line with our results, Martin-Garcia et al. [22, p. 3] found decreased emotional eating scores after 3 months of vigorous physical activity in a similar population. Sarvestani et al. [58] also found decreased emotional and external eating scores in response to a 6-month multi-disciplinary intervention. Altogether, these results strengthen the importance of behavioral interventions on eating behavior in pediatric obesity strategies. Importantly, in contrast with Sarvestani et al. [58], we did not find any increase in restraint score. This seems of particular interest in a weight loss perspective since restrained eating ignores appetite sensations and is therefore associated with binge eating. In that extent, Ho et al. previously demonstrated that a reduction in dietary restraint during a multi-component intervention among adolescents with obesity was associated with greater weight loss [59].

In a complementary analysis, we questioned whether the adolescents' initial eating behaviors could be associated with the success of the intervention. According to our results, there was a significant inverse correlation between adolescents' initial (baseline) cognitive restrained eating score and the percentage of weight loss. Similarly, the adolescents who lost less than 10% of their initial body weight were found to have a significantly higher cognitive restraint score compared to those whose weight loss exceeded 10% of their baseline weight. In contrast to popular beliefs, cognitive restriction does not seem to be a protective factor during weight management interventions. Several hypotheses may be considered to explain this observation. First, as suggested by the psychological theories on triggers overweight, cognitive restraint may be responsible for weight gain through overeating across binging [17]. Besides that, we found a significantly higher *ad libitum* food intake at the end of the program compared to baseline in restrained adolescents (*versus* non-restrained ones). As described in the literature, restrained eaters are more vulnerable to visual food cues [60] and are susceptible to increase their food consumption in a tempting situation; especially if they envision a way to compensate this overconsumption [61]. Indeed, Sim et al. [62] have recently demonstrated how exercise can be counterproductive among restrained eaters, when they considered physical activity as a compensatory health behavior, which “allowed” them to consume more calories. To that extent, cognitive restraint might be incriminated as a limited factor for weight loss achievement while it might, on the other hand, enhance the compliance to physical activity. In line with this hypothesis, we found a significantly higher fat-free mass variation between baseline and T2 in restrained (≈ +2 kg) compared with non-restrained eaters (≈ -0.6 kg, $p<0.05$), which could, according to the compensatory health belief model [63], be explained by the previously observed higher engagement in physical activity among restrained *versus* non-restrained individuals [64]. In light of this previous work, it would have been valuable to have complementary data regarding their engagement in physical activity.

In contrast to most of the studies, which used self-reported disinhibition rate with questionnaires, an objective measure of eating disinhibition with *ad libitum* buffet meals was used in the present study. *Ad libitum* buffets are tempting situations that present an array of palatable foods and request self-control. Indeed, in the context of this experiment, children’s ability to adjust their meal intake was solicited as well as self-discipline, as our design allowed children to overeat. Their consumption, therefore, reflects their disinhibition rate. The observed higher ad libitum energy intake (during our *ad libitum* test days) in restraint eaters is of particular importance and could explain the high rate of weight regain after weight loss interventions. Indeed, once the adolescents while leave the institution, they will be confronted to a high availability of food, which may challenge their eating self control and points out the necessity of nutritional education to prepare the post-intervention period. Further studies are needed to explore this post intervention period.

Aside from the behavioral adaptations that occur in restrained eaters, there is a combination of physiological characteristics that could explain the lower weight loss observed in restrained compared with non-restrained adolescents. Indeed, the previously underlined negative correlation between restrained score and leptin levels in both obese and lean individuals [65], [66] may explain the lower resting metabolic rate found among restrained eaters in previous works [67], and thus their lowest weight loss against the non-restrained ones. Moreover, from a neurocognitive perspective, restrained eating has been linked with weight gain through modification in the spontaneous neural activity in food reward and inhibitory brain regions [68]. In sum, even if the actual body of evidence seems to indicate a negative effect of cognitive restraint on weight management, further studies are needed.

Finally, the present study has to be interpreted in light of some limitations. Although we used *ad libitum* buffet meals as an objective measure of energy intake instead of self-reported diaries, our ecological setting might also compose a limitation. Indeed, the fact that the adolescents ate by small groups could have influenced their intake, which has not been assessed in the present work. The use of a convenience sample and the absence of a control group also have to be pointed out as potential limitations. Moreover, it would have been valuable to measure disinhibition using the Three Factor Eating Questionnaire; however, by the time of our study, the children version of the TFEQ (Bryant et al., 2018 Public Health Nutrition) was not validated yet, the French validation process being ongoing. We also could have added measurements of engagement in physical activity, perceptions about how demanding was the exercise or compensatory beliefs, as well as daily food intake (instead of just the three 24 hour records at baseline, middle and end of the intervention), which has not been done for practical reasons. Finally, while this study seems to be the largest one conducted so far that investigates dietary profile and eating behaviors in adolescents with obesity after such a long multidisciplinary weight loss intervention, physiological and neurocognitive investigations are missing to provide some potential explanatory mechanisms. Nonetheless, we considered in our analysis the individual trajectory/history of cognitive restraint and their implications. Indeed, as showed by our last analysis, some of the adolescents turned from unrestrained at baseline to restrained by the end of the program while others switched from restrained to unrestrained, with *ad libitum* energy intake being significantly different between these two subgroups. Further studies are thus needed in this area.

In conclusion, the present results showed increased *ad libitum* energy intake in response to a multidisciplinary weight loss program among adolescents with obesity, without modification of their daily appetite feeling profiles. Importantly, we found that the adolescents' dietary restraint score was negatively associated with their weight loss achievement in response to the intervention, with initially high restrained eaters losing less weight. Restrained eaters were also found to increase significantly more (compared to unrestrained eaters) their *ad libitum* food intake at the end of the weight loss program compared to baseline, which could potentially reflect their high disinhibition rate. Further longitudinal interventions are needed to determine the ability of specific eating behaviors in predicting good responders to a given weight loss intervention in adolescents with obesity.

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Declarations of interest

The authors have not conflict of interest to disclose.

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ÉTUDE II :

Effet de 4 mois de prise en charge multidisciplinaire combinant des exercices continus d'intensité modérée *versus* intermittents de haute intensité sur le comportement alimentaire et son contrôle chez l'adolescent en situation d'obésité : impact du profil psychologique vis-à-vis de l'alimentation.

Effect of HIIT *versus* MICT on body composition and energy intake in restrained and unrestrained adolescents with obesity

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Effect of HIIT *versus* MICT on body composition and energy intake in dietary restrained and unrestrained adolescents with obesity

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Abstract

Background. High Intensity Interval Training (HIIT) has been suggested as an effective alternative to traditional Moderate Intensity Continuous Training (MICT) that can yield improvements in a variety of health outcomes. Yet, despite the urgent need to find effective strategies for the treatment of pediatric obesity, only a few studies have addressed the impact of HIIT on eating behaviors and body composition.

Objective. This study aimed to compare the effect of HIIT *versus* MICT on eating behaviors in adolescents with obesity, and assess whether the participants' baseline dietary status is associated with the success of the intervention.

Methods. Forty-three adolescents with obesity were randomly assigned to a 16-week MICT or HIIT intervention. Body composition and 24-hour *ad libitum* energy intake were assessed at baseline (T0) and at the end of the program (T1). Restrained eating, emotional eating and external eating were assessed using DEBQ at baseline.

Results. Both interventions led to significant weight, BMI, and FM% reductions, with better improvements in FM% in the HIIT group; whereas 24-hour *ad libitum* energy intake increased to a similar extent in both groups. HIIT provides better body composition improvements over MICT, despite a similar increase in energy intake. Restrained eaters experienced less weight loss and smaller BMI reductions compared to unrestrained eaters adolescents, with higher baseline cognitively restrained adolescents showed greater increased of their *ad libitum* energy intake.

Conclusion. The present study reinforces the interest in chronic HIIT over MICT to improve body weight and body composition. It also suggests that HIIT and MICT have similar effects on eating behaviors. Finally, the success of the exercise-based intervention appears greater among unrestrained eaters compared to restrained eaters, independently of the training intensity.

Key findings.

-HIIT favors better body composition improvements compared with MICT

-Both MICT and HIIT increased *ad libitum* energy intake in adolescents with obesity

-Weight loss achievement is better among unrestrained eaters

Key words. Weight Loss, Multidisciplinary Intervention, Energy Intake, Dietary Profile, Restrained Eaters, Pediatric Obesity

Introduction

The prevalence of overweight and obesity among adolescents has reached about 30% in the United States and 25% in European Countries [1]. Since adolescents with obesity have higher morbidity and mortality risks compared to normal weight counterparts [2] and are of higher risk of becoming adults with obesity [3], pediatric obesity is of foremost public health concern. The development of effective weight management programs for adolescents who suffer from obesity is therefore a priority. The literature suggests that the best weight loss strategies should combine physical activity, nutritional approaches, and psychological support [4].

In regards to physical activity, High Intensity Interval Training (HIIT) has been suggested as a better alternative to traditional Moderate Intensity Continuous Training (MICT) in the treatment of pediatric obesity, since it promotes better improvement in health determinants [5], produces a lower rating of perceived exertion [6], and offers a more enjoyable and a time efficient modality of practice [7]. Moreover, acute HIIT has been shown to have beneficial effects on energy balance by both increasing energy expenditure and improving appetite control [8], [9]. Several studies have shown a positive effect of intensive exercise on energy intake, noting its potential anorexigenic effect in adolescents with obesity [10], [11]. This does not seem to occur with MICT [12]. Both physiological and neurocognitive pathways have been explored and identified to explain this effect of intensive exercise on energy intake. A rise of the main anorexigenic gastropeptides [13], [14], concomitantly with reduced neural responses to food cues [15], [16] and a decline in food reward [10], [17] after intensive exercise have been suggested mechanisms for the acute reduction in post-exercise energy intake. However, there is less agreement about the effect of chronic exercise on nutritional adaptations, especially in youth.

Although a recent meta-analysis found reduced daily energy intake in response to multicomponent weight-loss programs in adolescents with obesity [18], it also noted that most studies assessed energy intake as a secondary outcome using self-reported diaries, which have been shown to favor underestimation of food consumption in this population [19]. The authors therefore expressly identified the need for additional studies using alternative dietary assessment strategies with less potential bias [18]. Accordingly, we recently examined the *ad libitum* food intake response to a 10-month multicomponent weight-loss program in adolescents with obesity [20]. Contrary to the current body of evidence, suggesting that multi-component interventions promote decreased daily energy intake in adolescents with obesity [21]–[23], our results showed a significantly greater daily *ad libitum* energy intake (+246 kcal, p<0.001) at the end of the intervention compared to baseline [20]. These results clearly underline the importance of objective methods to assess nutritional adaptations to weight loss in youth and the need to consider the adolescents' individual eating behavior traits as a screening tool for identifying adverse responders to weight loss interventions. Though it seems counterintuitive, high levels of cognitive dietary restraint (perceived ongoing effort to limit dietary intake to manage body weight) do not appear advantageous in weight loss settings. Previous work has demonstrated that the most cognitively restrained eaters appeared to be the most vulnerable to increased energy intake in tempting situations [24], such as *ad libitum* buffet meals. This is in line with previous studies showing that the efficacy of exercise-induced weight management depends on the individuals' dieting status [25].

To date, we found only one study that questioned the effect of high *versus* low intensity exercise-based weight loss interventions on energy intake in adolescents with obesity, showing significantly reduced food consumption after 12 weeks of both high and low intensity training, with a greater effect in the high intensity group [23]. According to their results, this decreased energy intake could be explain by reduced fasting ghrelin and increased PYY concentrations. However, as previously noted, the authors used self-reported food diaries to assess energy intake, and based their high intensity intervention on the adolescents' first ventilatory threshold, which corresponds to a relatively moderate intensity in this population. These limitations, therefore, have restricted the ability to draw conclusions regarding the effects of chronic exercise programs on energy intake in youth.

In this context, the current study aimed to compare the nutritional responses to a 16-week multi-component program involving either HIIT or MICT, using objective measures of energy intake and considering baseline eating behavior traits in adolescents with obesity

Methods

Participants

A total of 43 adolescents (mean age: 13.6 (1.5) years, 72% female) with obesity as defined by Cole et al. [26] (mean BMI z-score: 2.3 (0.3); BMI percentile: 98.9 (0.8)) were enrolled in this study. Convenience sampling was employed based on our clinical recruitment through local pediatrician consultations. To be included, participants had to: i) be aged between 11 and 15 years; ii) be between Tanner stage 3 to 5 iii) present a BMI greater than or equal to the 95th percentile for their gender and age; iv) be free of any medication that could interact with the protocol (e.g., thyroid medication, stimulant medication, medication for diabetes); v) present no contraindication to physical activity; vi) self-report less than 2 hours of physical activity per week (International Physical Activity Questionnaire – IPAQ). All of the adolescents and their legal representatives received information sheets and signed consent forms as requested by the local ethical authorities.

Protocol design

After a medical inclusion visit conducted by a pediatrician, the adolescents were enrolled in a 16-week residential multidisciplinary weight loss program through a local Pediatric Obesity Center (Service Sesame, Centre Médicale Infantile de Romagnat, France). They were randomly allocated to either the MICT (n=21) or HIIT (n=22) group for 16 weeks (permuted-block randomization conducted using a computer-generated random allocation (Stata software, version 13, StataCorp, College Station, US)). Maturation status (assessed by the physician using the Tanner stages) and eating behavior traits (assessed using the Dutch Eating Behavior Questionnaire) were evaluated during the first medical visit. Individual aerobic capacity was assessed at baseline (VO_2peak). Anthropometric measurements, body composition (dual-energy X-ray absorptiometry), daily energy intake (*ad libitum* buffet meals), and appetite sensations (visual analogue scales) were assessed before (T0) and after (T1) the 16-week program. This study was conducted in accordance with the Helsinki declaration and received an ethical agreement from official authorities (CPP Sud Est VI: AU1178; Clinical Trial NCT02482220).

Measurements

Anthropometric characteristics and body composition

At baseline (T0) and at the end of the program (T1), body weight and height were recorded to the nearest 0.1 kg and 0.5 cm, respectively, while wearing light clothes and bare-footed, using a digital scale and a standard wall-mounted stadiometer. Body Mass Index (BMI) was calculated as weight (kg) divided by height squared (m^2). BMI was reported in the sex- and age-specific French reference curves for BMI percentile. Fat mass (FM) and fat-free mass (FFM) were assessed, in the fasted state, by dual-energy X-ray absorptiometry (DXA) following standardized procedures (QDR4500A scanner, Hologic, Waltham, MA, USA).

Eating behavior traits

Eating behavior traits were assessed at baseline using the Dutch Eating Behavior Questionnaire (DEBQ) [27]. Three domains were evaluated: restrained eating (individuals' efforts to limit their food intake to control body weight or to promote weight loss; 10 items), emotional eating (excessive eating in response to negative moods; 13 items) and external eating (eating in response to food-related stimuli, regardless of the internal state of hunger or satiety; 10 items). Participants filled the 33 items in a six-point Likert scale (never (1), seldom (2), sometimes (3), often (4), very often (5) and not relevant (0)). Their answers were coded following the instructions given by Lluch et al. [27]. Means for each domain were calculated, with higher scores indicating greater endorsement of the eating behavior and mean scores higher than three (3) categorizing adolescents as restrained, emotional and/or external eaters. This questionnaire has been previously validated in its French version [27].

Maximal oxygen uptake test (VO2)

Each subject performed a $\dot{V}O_2$peak test on a traditional concentric ergometer [22]. The initial power was set at 30W during 3 minutes, followed by a 15W increment every minute until exhaustion. The adolescents were strongly encouraged by the experimenters throughout the test to perform their maximal effort. Cardiac electrical activity (Ultima SeriesTM, Saint Paul, MN) and heart rate (Polar V800) were monitored, in addition to breath by breath gas exchange (BreezeSuite Software, Saint Paul, MN) to determine $\dot{V}O_2$ and CO_2 (Carbon Dioxide) production ($\dot{V}CO_2$). Volumes and gases were calibrated before each test. Maximal criteria were: heart rate >90% of the theoretical maximum heart rate ($210 - 0.65 \times$ age), Respiratory Exchange Ratio (RER = $\dot{V}CO_2/\dot{V}O_2$) > 1.1 and/or $\dot{V}O_2$ plateau. The $\dot{V}O_2$peak was defined as the average of the last 30 s of exercise before exhaustion.

Ad libitum energy intake

Daily *ad libitum* energy intake was assessed during two single test days: at baseline (T0) and at the end of the program (T1). After a standardized breakfast meeting recommendations for their age (≈500 kcal) [28], participants were offered *ad libitum* lunch and dinner buffet-type meals (as detailed in Table 1). The content of the buffets was determined based on the individual food preferences and eating habits of each participant. Top rated items, disliked items, and items liked but not usually consumed were excluded to avoid over-, under- and occasional consumption. Adolescents were told to eat until they felt comfortably satiated. Food items were presented in abundance and adolescents could consume as much they wanted. All food was weighed by the experimenter, and the macronutrient distribution (proportion of fat, carbohydrate and protein) and total energy intake (kcal) were calculated using the software Bilnut 4.0. This methodology has been previously validated and published by our research team [29].

Table 1. Composition of meals.

Breakfast	Lunch	Dinner
	Beef steak	Ham/turkey
Bread	Pasta	Beans
Butter	Mustard	Mashed potato
Marmalade	Cheese	Cheese
Fruit juice/fruit	Yogurt	Yogurt
Yoghurt/milk	Compote	Compote
	Fruits	Fruits
	Bread	Bread

Subjective appetite sensations

Appetite sensations were assessed throughout the "*ad libitum* days" at baseline (T0) and at the end of the program (T1) using visual analogue scales (150 mm scales). Participants reported their hunger, fullness, desire to eat and prospective food consumption at regular intervals: before and immediately after breakfast, 30 minutes and 60 minutes after breakfast, before and after the experimental condition (CON or HIIE), before and immediately after lunch, 30 minutes and 60 minutes after lunch, before and immediately after dinner. This method has been previously validated [30].

Multidisciplinary weight loss program

The 16-week residential multidisciplinary weight loss program combined physical activity (4/week), nutritional education (2/month) and psychological support (1/month). During the intervention, the adolescents were prescribed a isocaloric diet based on their age and sex recommendations (Murphy & Poos, 2002). Physical activity included aquatic activities (1/week, activities such as water aerobics and various games realized while immersed), leisure-time activities (e.g., soccer and basketball games and exercises, 1/week) and either MICT + strength training or HIIT + strength training

(2/week). The MICT group (n=21) trained 45 minutes two times per week on ergometer bicycle at 60% of their initial VO_2peak, followed by strength training. The HIIT group (n=22) performed 15 minutes intermittent exercise two times per week on ergometer bicycle, alternating 30 seconds intense exercise and 30 seconds active recovery (free but compulsory pedaling), also followed by strength training. The intensity for HIIT followed a progressively increased from 75% of baseline VO_2peak, ending at 90%. The cycling intensity of both HIIT and MICT was controlled using the mechanical workload settings of the ergometer and double-checked via live heart rate readings, based on the results from the baseline VO_2peak test. Strength training was also gradually increased with the number of repetitions and the load. Apart from the differences in the exercise prescription (MICT *versus* HIIT), adolescents received the same attention and medical care throughout residence. While the leisure-time and aquatic activities were performed collectively (mixing adolescents from both groups), the HIIT and MICT specific sessions were conducted separately. Importantly, there was no difference between groups for VO_2 peak at baseline (HIIT: 27.8 ± 6.0 ml/min/kg; MICT: 25.1 ± 5.5 ml/min/kg).

Statistical analysis

Statistical analyses were performed using Stata software, Version 13 (StataCorp, College Station, TX, US). All tests were two-sided, with a Type I error set at 0.05. Continuous data was expressed as mean ± standard deviation (SD) or median [interquartile range] according to statistical distribution. The assumption of normality was assessed by using the Kolmogorov-Smirnov test. Random-effects models for repeated data were performed to study the evolution between T0 and T1 for weight, body composition, RMR, eating behaviors, *ad libitum* energy intake and macronutrient consumption. For appetite sensations, area under the curves (AUC) based on the trapezoid methods was also analyzed. Then, the following fixed effects were evaluate: time, group (notably HIIT vs. MICT) and time x group interaction, taking into account between and within patient variability (subject as random-effect). The normality of residuals from these models was studied using the Shapiro-Wilk test. When appropriate, a logarithmic transformation was proposed to achieve the normality of dependent outcome. Concerning non-repeated measures, quantitative variables were compared between groups by means of Student t-test or Mann-Whitney test when the assumptions of t-test were not met (normality and homoscedasticity analyzed using the Fisher-Snedecor test). These analyses were conducted to compare baseline parameters (e.g., weight, body composition) and their variation at the end of the 16-weeks intervention between groups (HIIT vs. MICT, restrained vs. non-restrained eaters, emotional vs. non-emotional eaters, and external vs. non-external eaters). As proposed by some statisticians (Feise, 2002; Rothman, 1990) a particular focus will be given to the magnitude of differences, in addition to inferential statistical tests expressed using p-values. The results were expressed using Hedges' effect size and 95% confidence interval and were interpreted according to Cohen's rules of thumb with defined effect-size bounds as: small (ES: 0.2), medium (ES: 0.5) and large (ES: 0.8: grossly perceptible and therefore large). No statistically significant effects of age, gender and maturation effect were observed.

Results

From the initial 50 children enrolled (25 in each group), 43 completed the 16-week multidisciplinary program MICT (n=21) or HIIT (n=22). None of the seven drop-out reasons were related to the study itself, but were due to family, disciplinary or school-related reasons.

Anthropometric characteristics and body composition are presented in Table 2. Body mass and BMI were similarly reduced in both groups ($p<0.0001$) with no change in FFM. There was a greater reduction in FM percent in the HIIT group compared with the MICT group (interaction group x time $p=0.046$; t-test for delta=0.027).

Table 2. Effects of HIIT and MICT on anthropometry and body composition in adolescents with obesity.

		Baseline Mean (SD)	16 weeks Mean (SD)	Delta Mean (SD)	Time effect	Group effect	Inter-action
Weight (kg)	MICT	97.2 (15.5)	92.9 (13.6)***	-6.54 (3.4)	<0.0001	0.190	0.568
	HIIT	92.5 (14.5)	85.4 (14.1)***	-7.12 (3.7)			
BMI (kg/m^2)	MICT	36.6 (4.3)	34.7 (3.7)***	-2.26 (1.3)	<0.0001	0.088	0.069
	HIIT	34.8 (4.5)	31.8 (4.7)***	-3.03 (1.4)			
FM (%)	MICT	42.4 (3.8)	39.4 (5.1)***	-2.78 (1.8)	<0.0001	0.009	0.046
	HIIT	39.6 (5.3)	34.9 (5.6)$^{***\$}$	-4.72 (3.6)^{A}			
FFM (kg)	MICT	54.7 (8.2)	53.6 (7.4)*	-1.09 (2.1)	0.164	0.875	0.478
	HIIT	54.3 (8.4)	53.9 (8.0)	-0.27 (3.7)			

HIIT: High Intensity Interval Training; MICT: Moderate Intensity Interval Training; BMI: Body Mass Index; FM: Fat Mass; FFM: Fat Free Mass; *: significantly different from baseline with $p<0.05$; ***: significantly different from baseline with $p<0.001$; $^{\$}$: significantly different from MICT at same time point with $p<0.05$; A: significantly different between MICT and HIIT

As shown in Table 3, there were differences at baseline between MICT and HIIT group for some food intake parameters. However, no interaction (between group and time) was found for the following variables: total energy intake, lunch energy intake, dinner energy intake, carbohydrate, protein and fat consumption (in grams and percentage). Total energy intake, lunch energy intake, and dinner energy intake all similarly increased in both groups after the 16-week multidisciplinary intervention (time effect<0.0001), with no change in the macronutrient distribution over time.

Table 3. Effects of HIIT and MICT on food intake in adolescents with obesity.

	Baseline Mean (SD)	16 weeks Mean (SD)	Delta Mean (SD)	Hedges's	Time effect	Group effect	Interaction
Total EI (kcal/day)							
MICT	1752.6 (325.9)	2406.6 (462.2) ***	615.2 (314.4)	0.06	<0.0001	0.001	0.960
HIIT	2126.7 (410.5) $	2770.5 (503.0) ***$	643.7 (543.9)	[-0.56; 0.689]			
Lunch EI (kcal/day)							
MICT	721.4 (181.8)	1122.1 (305.0) ***	377.7 (184.3)	0.14	<0.0001	<0.0001	0.933
HIIT	1003.9 (258.0) $$	1385.5 (356.4) ***$$	381.6 (335.0)	[-0.60; 0.62]			
Dinner EI (kcal/day)							
MICT	527.2 (215.4)	780.4 (288.7) ***	237.4 (269.3)	0.08	<0.0001	0.082	0.884
HIIT	618.8 (205.5)	880.9 (234.8) ***	262.1 (308.2)	[-0.53; 0.69]			
CHO %							
MICT	47.5 (5.3)	46.1 (7.5)	-1.8 (6.2)	0.17	0.845	0.010	0.658
HIIT	50.9 (5.6)	50.4 (6.5)	-0.5 (8.5)	[-0.45; 0.78]			
Fat %							
MICT	31.1 (5.0)	33.1 (6.5) *	2.4 (4.9)	-0.31	0.612	0.003	0.362
HIIT	27.7 (5.1) $	28.4 (5.0) $	0.7 (5.7)	[-0.92; 0.31]			
Proteins %							
MICT	20.7 (1.6)	20.3 (1.8)	-0.3 (2.4)	0.04	0.673	0.953	0.881
HIIT	20.6 (3.1)	20.4 (3.4)	-0.2 (4.70)	[-0.57; 0.65]			
CHO (g/day)							
MICT	149.3 (44.6)	221.2 (67.8) ***	66.3 (48.2)	0.17	<0.0001	<0.0001	0.685
HIIT	206.4 (57.1) $$	283.4 (63.1) ***$$	77.0 (70.0)	[-0.44; 0.78]			
Fat (g/day)							
MICT	42.7 (13.2)	69.3 (20.2) ***	25.7 (15.9)	-0.16	<0.0001	0.241	0.525
HIIT	50.0 (14.8)	72.2 (22.3) ***	22.2 (24.0)	[-0.78; 0.45]			
Proteins (g/day)							
MICT	64.2 (16.1)	96.0 (22.0) ***	29.9 (16.5)	0.09	<0.0001	0.001	0.878
HIIT	83.4 (24.1)$	115.8 (32.4) ***$	32.5 (35.4)	[-0.52; 0.70]			

HIIT: High Intensity Interval Training; MICT: Moderate Intensity Interval Training; EI: energy intake; CHO: carbohydrate; ***: significantly different from baseline with p<0.001; $: significantly different from MICT at same time with p<0.05; $$: significantly different from MICT at same time with p<0.01

In regards to appetite sensations (see Table 4), there was a significant effect of time in the intervention, independent of the training intensity, for fasting hunger and fasting desire to eat (both increased, time effect: 0.039 and 0.046). No significant time effect or interaction was found for fasting satiety and fasting prospective food consumption, or for daily hunger, satiety, prospective food consumption and desire to eat.

Table 4. Effects of HIIT and MICT on appetite sensations in adolescents with obesity.

	Baseline Mean (SD)	16 weeks Mean (SD)	Delta Mean (SD)	Hedges's	Time effect	Group effect	Interaction
Fasting Hunger							
MICT	52.9 (42.2)	71.1 (47.4)	10.8 (45.9)	0.25	0.039	0.007	0.545
HIIT	79.8 (38.2)	105.0 (50.7) *	23.2 (49.3)	[-0.37; 0.89]			
Fasting Satiety							
MICT	40.7 (58.2)	53.0 (50.7)	14.5 (62.6)	-0.13	0.269	0.026	0.791
HIIT	18.6 (34.6)	26.5 (40.0)	7.0 (53.6)	[-0.77; 0.52]			
Fasting PFC							
MICT	51.6 (34.0)	68.4 (36.0)	8.8 (39.8)	0.14	0.113	0.001	0.804
HIIT	84.9 (44.3) $	103.6 (36.8) $	14.7 (42.2)	[-0.51; 0.79]			
Fasting Desire To Eat							
MICT	55.9 (45.9)	88.0 (36.4) *	19.9 (44.7)	-0.25	0.046	0.003	0.268
HIIT	97.3 (43.2) $	111.1 (38.1)	9.2 (38.3)	[-0.90; 0.40]			
Total Hunger							
MICT	21944.1 (14229.4)	29570.0 (15093.5)	6537.0 (17896.8)	-0.08	0.059	0.001	0.707
HIIT	33371.5 (11605.4) $	38872.6 (11870.6)	5203.2 (16004.4)	[-0.73; 0.57]			
Total Satiety							
MICT	59267.2 (22405.1)	64599.6 (17062.9)	6410.0 (23035.7)	0.08	0.153	0.030	0.907
HIIT	49132.6 (18726.4)	54843.7 (13613.9)	4732.5 (23035.7)	[-0.60; 0.75]			
Total PFC							
MICT	21841.1 (17504.0)	27778.5 (10500.4)	3882.3 (19454.3)	0.05	0.198	<0.000	0.976
HIIT	3218.6 (13178.5) $	38884.3 (12359.5) $	4868.8 (17438.3)	[-0.61; 0.71]			
Total Desire To Eat							
MICT	23587.8 (19173.6)	28215.6 (10670.5)	1951.0 (19794.0)	0.03	0.543	0.001	0.840
HIIT	35717.9 (13974.6)	38811.2 (11936.6)	2435.7 (16580.0)	[-0.63; 0.69]			

HIIT: High Intensity Interval Training; MICT: Moderate Intensity Interval Training; PFC: Prospective Food Consumption; *: significantly different from baseline with p<0.05; $: significantly different from MICT at same time with p<0.05

Baseline restraint, emotional eating, and external eating scores were not different between groups (see Table 5). 42.2% of the adolescents were classified as restrained eaters, 28.9% as emotional eaters and 15.5% as external eaters.

Table 5. Eating behavior profile scores at baseline.

	MICT Mean (SD)	HIIT Mean (SD)	*p* value	TOTAL Mean (SD)	% of children with score ≥3
Restraint score	3.0 (0.6)	2.9 (0.6)	0.712	2.9 (0.6)	42.2%
Emotional eating score	2.6 (1.1)	2.1 (1.0)	0.153	2.3 (1.1)	28.9%
External eating score	2.5 (0.5)	2.6 (0.7)	0.749	2.5 (0.6)	15.5%

HIIT: High Intensity Interval Training; MICT: Moderate Intensity Interval Training

No difference between restrained and unrestrained adolescents was found for age, initial weight, initial BMI, initial FM%, initial FFM, and initial total energy intake, carbohydrate, fat and protein consumption (results not shown). However, as shown in figure 1, weight loss and BMI reduction were greater among unrestrained eaters compared to restrained eaters, independently of the training intensity.

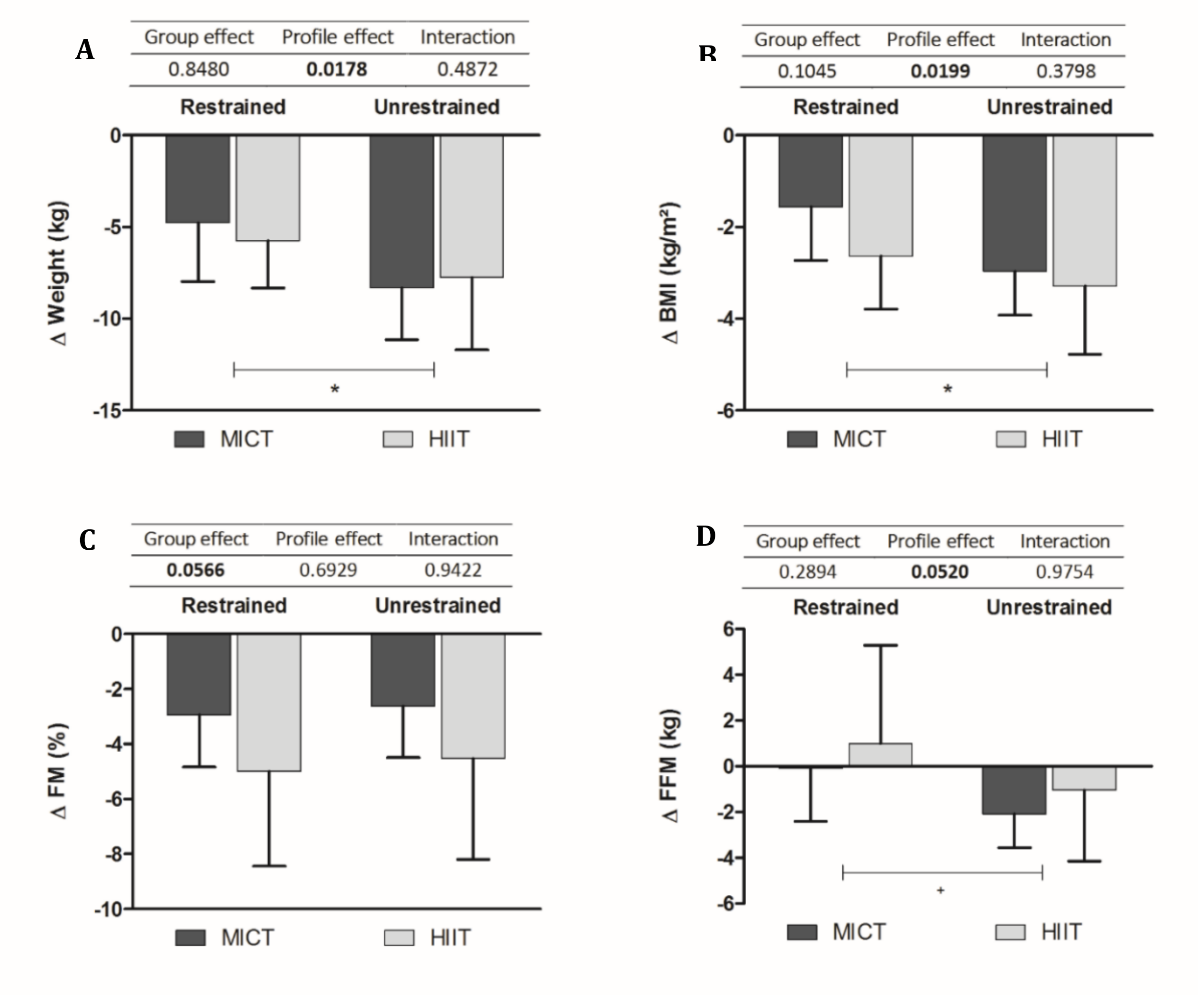


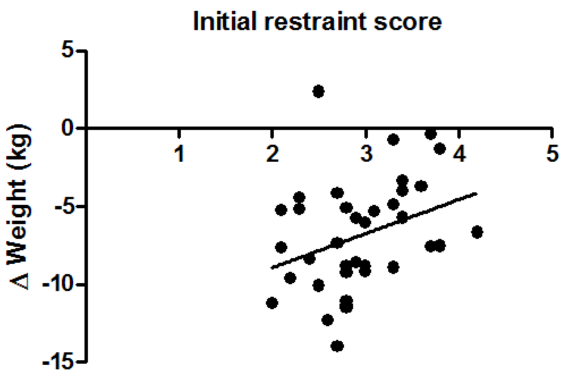
Figure 1. Body composition change from baseline to 16 weeks among MICT and HIIT groups, separated by baseline eating behavior profile. A: Weight; B: BMI; C: FM; D: FFM. *: p<0.05; +: p<0.06; HIIT: High Intensity Interval Training; MICT: Moderate Intensity Interval Training

Restrained eaters (n=16) lost 5.26 (0.71) kg and 2.10 (0.31) kg/m^2, whereas unrestrained eaters (n=23) lost 7.95 (0.74) kg and 3.18 (0.27) kg/m^2 (p= 0.018 for weight and p= 0.020

for BMI). Moreover, unrestrained eaters tended to lose more FFM (-1.41 (0.56) kg) compared to restrained eaters (+0.45 (0.84) kg) (p=0.052).

We found no interaction, group, or eating behavior profile effect for total EI, appetite sensations, carbohydrate, fat, and protein consumption between baseline and the end of the intervention (results not shown).

There were significant associations between the initial restraint score and variations in body weight and lunch *ad libitum* energy intake (no significant association with dinner and total *ad libitum* energy intake) from baseline to 16 weeks (respective r=0.33 and 0.34 with p<0.05, see figure 2).



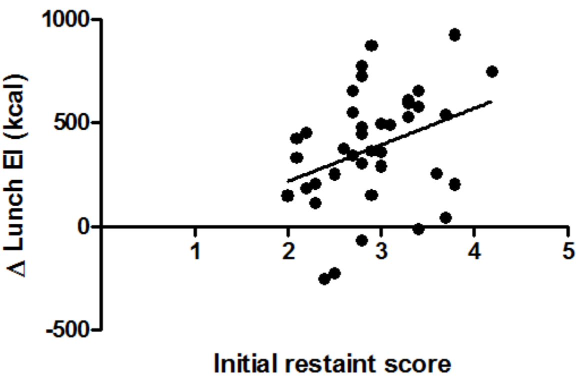


Figure 2. Associations between initial restraint score and variations in weight (A) and lunch *ad libitum* energy intake (B) from baseline to 16 weeks**.** A: r=0.33, p=0.045; B: r=0.34, p=0.03; Δ: delta from baseline to 16 weeks

Discussion

The aims of this study were, first, to compare the effect of two multidisciplinary weight loss programs that incorporated either HIIT or MICT, on body weight and body composition in adolescents with obesity and then, to determine whether individual eating behavior profiles were associated with the success of the intervention. Spontaneous daily *ad libitum* energy intake similarly increased in both groups over the 16-week program (about 615 kcal in MICT and 644 kcal in HIIT group), with concomitant fasting hunger and fasting desire to eat. Importantly, the intervention appeared to be more successful among unrestrained eaters compared to restrained eaters, independently of the exercise training intensity.

As expected, both interventions led to significant weight, BMI and FM% reductions. In accordance with the literature [4], our results confirm that combining physical activity, nutritional education, and psychological support is an efficient anti-obesity strategy in youth. Yet, our results bring new insights regarding the role of exercise in multidisciplinary weight loss programs, examining effects of HIIT *versus* MICT on body composition and appetite regulation in adolescents with obesity. Several recent meta-analyses [32] showed comparable improvements between the two exercise prescriptions in body composition in adults with obesity. Our results, however, demonstrate better improvements in FM% in the HIIT group (-4.7%) compared with MICT (-2.8%). Moreover, although not statistically significant, FFM showed a slight decrease in the MICT group only (MICT: -1.1 kg *versus* HIIT: -0.3 kg). Furthermore, HIIT provides a time-efficient alternative, since it requires ~70% less training time when compared with MICT (15 minutes *versus* 45 minutes per week in the present study). Taken together, these results strengthened the justification for HIIT as part of weight loss interventions in adolescents with obesity.

Few studies have addressed the impact of chronic exercise on eating behaviors (food intake and subjective feelings of appetite) in youth with obesity. Schwartz et al. were the first to demonstrate in a systematic review and meta-analysis that chronic exercise may decrease daily energy intake in adolescents with obesity [18]. However, the authors noted several important limitations, including the lack of direct measures of food, total energy, or macronutrient intakes, and no consideration of appetitive ratings or eating behavior traits. Unlike previous studies, we used an objective and validated measure of food intake

[29]. *Ad libitum* buffets are tempting situations that present an array of moderately palatable foods and allow children to overeat. This is a strength relative to self-reported dietary recalls that have been shown to provide under-reported food intake, especially among adolescents with obesity [19]. This major discrepancy between the methodologies used to assess energy intake could explain our results showing an increase energy intake following the 16-week intervention. We found that lunch and dinner, as well as total *ad libitum* energy intake over 24 hours, increased after both the HIIT and MICT interventions, with no difference between groups. Participants in both groups increased intake (grams) of carbohydrate, fat, and protein similarly. The proportions of macronutrient intake remained approximately 50%, 30% and 20% for carbohydrates, fat, and protein respectively, across both time points in each group, highlighting no specific change in macronutrient consumption patterns in response to chronic exercise.

Several mechanisms may explain why multi-component-induced weight loss is accompanied by an increase in energy intake. First, the increased food consumption observed in our study may result from an upregulation of appetite hormones such as ghrelin, the main orexigenic hormone, as an adaptive response to energy deficit and weight loss [34], [35]. In their work, Gueugnon et al. [36] found increased fasting ghrelin concentrations after a 9-month multidisciplinary weight loss intervention in adolescents with obesity. Their results are reinforced by the increased hunger profile and reduced satiety profile observed by King and colleagues after a 6-week weight loss intervention in a similar population [37]. According to the authors, decreasing daily energy intake while increasing energy expenditure through exercise is effective in inducing weight loss, but favors a sensitization to appetitive signals in youth with obesity [37]. In line with these results, we found fasting hunger and fasting desire to eat increased after the 16-week weight loss intervention in both groups. Other than the homeostatic processes of appetite control, which increase the orexigenic drive to eat, changes in hedonic processes also occur in response to weight loss [38]. In this regard, Finlayson et al. highlighted changes in the reward value of the food after both acute and chronic exercise [39], [40]. Weight loss could therefore lead to increased energy intake by enhancing liking and wanting for food.

Strategies used to lose weight involve both decreased energy intake and increased energy expenditure. As physical activity is the major modifiable component of energy expenditure, it appears to be a valuable way to create an energy deficit. However, several studies demonstrated a counterintuitive effect of physical activity, increasing energy intake by an amount that exceeded energy expended. Sonneville and Gortmaker [41] found, in a prospective observational study on 538 youth, that a 1-hour increase in physical activity per day was associated with 292 kcal increase in total energy intake. Their results assumed then that physical activity could lead to an energy surplus. In particular, this overcompensation seems to occur in cognitively restrained eaters. Indeed, Sim et al. [42] have recently demonstrated how exercise can be counterproductive among restrained eaters, when they considered physical activity as a compensatory health behavior, which “allowed” them to consume more calories. Cognitive restraint could be incriminated as a limiting factor for weight loss achievement. Importantly, our previous work in youth with obesity [20] demonstrated that a 10-month multidisciplinary weight loss intervention was also less effective among restrained eaters (compared to unrestrained eaters), with initially high-restrained eaters losing less weight and experiencing a greater increase of their *ad libitum* energy intake in response to the program. In line with these results, the present study showed poorer weight loss achievement and smaller BMI reduction in restrained eaters compared to unrestrained eaters. The average body weight and BMI reductions were -5kg and -2kg/m^2, respectively, in restrained eaters *versus* -8kg and -3kg/m^2 in unrestrained eaters. Similarly, adolescents with higher baseline cognitive restraint scores showed reduced weight-loss in response to both interventions.

Dieting in adolescents is widespread, especially among those with obesity, with higher reported sociocultural and familial pressures to reach an ideal body weight [43], [44]. In the present study, 42% of the adolescents reported a high level (>3) of cognitive restraint. However, many studies suggested that restraint around food has adverse effects [45], [46]. In adolescents, dietary restraint has been associated with food preoccupation, tendency to overeat, binge eating and other food-related disorders [47]. In that regard, we found a significant association between baseline cognitive restraint and the increase in lunch *ad libitum* energy intake, with the more cognitively restrained eaters showing a greater increase of their *ad libitum* energy intake at lunch. This association supports previous findings suggesting a link between cognitive restraint and binge eating potentially contributing to long-term weight gain.

In addition, 29% of our participants reported a high level of emotional eating and 16% reported high external eating, relying more on external cues and emotions rather than internal appetite sensations to regulate their energy intake. Previous studies demonstrated a positive effect of multidisciplinary interventions on reported eating behavior traits (decreasing emotional and/or external eating) [20], [48]–[50]. Unfortunately, we did not administer the Dutch Eating Behavior Questionnaire post-intervention to examine the effects of different exercise components. Therefore, further studies examining the beneficial effects of chronic exercise on eating behavior in youth with obesity are justified. In fact, many behaviors are carried from childhood into adulthood, and unhealthy eating habits during adolescence could have adverse effects across the lifespan. Studying the evolution of eating habits and dieting status during a chronic multi-component weight loss program should therefore be a priority in clinical practice and the research area.

In the current study, we were the first to evaluate the differences between two multi-component weight loss programs including either HIIT or MICT among adolescents with obesity, with robust measures of appetite control and energy intake. Indeed, the measurements tackled several aspects of appetite, including objective measures of energy intake, subjective feelings of appetite sensations, and eating behavior traits of the participants. However, the present study has also several limitations. Mainly, we did not evaluate binge-eating tendencies, which did not allow us to establish any link between restraint and uncontrolled eating, and we did not measure the evolution of eating behaviors throughout the program. Similarly, we did not take into account the high inter-individual response variability in body composition and compensatory behaviors to exercise, warranting additional investigation with a larger sample size. Finally, as we did not assess habitual physical activity across the intervention, and therefore we cannot examine the potential compensation effect in response to scheduled exercise.

To conclude, the present study reinforces the interest in HIIT over MICT when it comes to body weight and body composition, while also suggesting that HIIT and MICT have similar effects on energy intake and appetite regulation in adolescents with obesity. Independently of the intensity and structure of the exercise program, energy intake, fasting hunger and desire to eat increased, concomitantly with weight loss. Further research is needed to establish the most beneficial protocol for these patients by taking into account their individual eating behavior traits, as more cognitively restrained eaters were the most "resistant" to weight loss. Considering these findings, dietary status appears to be a key determinant in the success of weight loss programs in adolescents with obesity.

Conflicts of interest statement

The authors declare no conflicts of interest.

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involved in this work, particularly Mr Bonnet Jean-Michel who supervised the interventions. Yves Boirie and Martine Duclos conceived the experiment. Maud Miguet, Lore Metz, Marwa Khammassi, Valérie Julian, Charlotte Cardenoux and David Thivel carried out experiments. Bruno Pereira analysed data. Maud Miguet, Nicole Fearnbach and David Thivel searched literature and wrote the manuscript. All authors had final approval of the submitted published versions.

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ÉTUDE III :

Effet d'un exercice intermittent de haute intensité sur la prise alimentaire et le système de la récompense chez l'adolescent en situation d'obésité : impact du degré d'obésité.

Appetite, energy intake and food reward responses to an acute high intensity interval exercise in adolescents with obesity

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Abstract

Background. High Intensity Interval Exercise (HIIE) is currently advocated for its beneficial effect on body composition and cardio-metabolic health in children and adolescents with obesity; however its impact on appetite control and food intake remains unknown. The aim of the present study was to examine the effect of a single HIIE session on subsequent energy intake, appetite feelings and food reward in adolescents with obesity.

Methods. Using a randomized cross-over design, *ad libitum* energy intake, subjective appetite, and food reward were examined in 33 adolescents with obesity (13.0 (± 0.9) years) following an acute high-intensity interval exercise (HIIE) *versus* a rest condition (CON). Absolute and relative energy intakes were measured from an *ad libitum* lunch meal 30 minutes after exercise or rest. Food reward was assessed using the Leeds Food Preference Questionnaire before and after the test meal. Appetite feelings were assessed using visual analogue scales at regular intervals throughout the day.

Results. *Ad libitum* food intake was significantly reduced after HIIE (lunch meal: -7 (± 23.7)%; p=0.014 and whole day: -4 (± 14.7)%; p=0.044), despite unchanged appetite feelings. HIIE was also found to decrease *ad libitum* meal food reward in adolescents with obesity: fat relative preference (from 3.3 (± 9.5) to 0.1 (± 8.0); p=0.03), sweet taste relative preference (from -0.8 (± 13.9) to -5.0 (± 11.8); p=0.02) and fat implicit wanting (from 22.3 (± 55.7) to -13.2 (± 58.5); p=0.01) were significantly decreased in response to

the *ad libitum* meal on HIIE. When considering the degree of obesity, it appears that the adolescents with higher BMI and higher fat mass percentage showed greater food intake reductions in response to HIIE (-21 (± 15)% for the third BMI tertile *versus* +8 (± 30)% for the first BMI tertile p=0.004; -15 (± 21)% for the third fat mass tertile *versus* +8 (± 28)% for the first fat mass tertile p=0.017).

Conclusion. A single HIIE session resulted in reduced subsequent energy intake and food reward in adolescents with obesity. Our results also seem to indicate that these nutritional responses depend on the adolescents' degree of obesity with a greater anorexigenic effect observed with higher obesity.

Key words. High Intensity Interval Exercise; Appetite; Energy Intake, Pediatric Obesity

Introduction

There is an alarming progression of pediatric obesity with one out of four children concerned in European countries [1]. This obesity pandemic results in part from an energy imbalance between energy intake and expenditure, favored by the increasing availability of palatable high-fat food, concomitantly with a clear decline in children's physical activity and progression of the time they spend sedentary [2]. Anti-obesity strategies that consider both sides of energy balance are therefore needed.

Evidence has shown that exercise energy expenditure and energy intake are loosely coupled variables, therefore we need a better understanding of their interactions [3]. Since the 1950s, many works have attempted to assess the role of daily activity-induced energy expenditure (from vigorous physical activity to sedentary behaviors) on energy intake in adults [4]. A recent systematic review in adults revealed there to be a better control of energy intake in active compared to inactive people, while individuals with very low levels of physical activity and high rates of sedentary behavior seem to suffer from a non-regulated control of food intake [5].

Although this relationship between exercise and energy intake has been mainly studied in adults for the last couple of decades, more attention has been recently paid to this question among children and adolescents, lean or obese [6]–[8]. According to the available evidence, while an acute bout of exercise does not seem to alter subsequent food consumption in lean children and adolescents [9], [10], an acute bout of intensive exercise (above 70% of the adolescent's maximal capacities) has been shown to significantly decrease food intake at the following meal in those with obesity [11]. This effect has been attributed to higher post-exercise anorexigenic gastrointestinal peptide concentrations [12] (such as peptide YY, glucagon-like peptide-1, and pancreatic polypeptide) and lower neurocognitive responses to food cues [13].

High-Intensity Interval Exercise (HIIE) has recently been described as an efficient exercise modality in adolescents with obesity, producing a lower perceived exertion and being at least as effective as moderate-continuous training to improve their body composition and metabolic profile [14]. Recent studies conducted in overweight adults also suggest that HIIE has similar effects on appetite sensations and hedonic liking and wanting for food than moderate intensity interval training [15]. Thus, HIIE does not appear to lead to a reward-induced increase in food intake [15]. The same team also found that a 4-week HIIE intervention was able to reduce hunger and the desire to eat, as well as to limit food compensation compared to a moderate-intensity program that tended to increase the preference for high fat food in overweight adults [16]. To our knowledge, there is so far no study that has examined the effect of HIIE on subsequent energy intake and appetite feelings in children and adolescents with obesity. Morris and collaborators recently examined the effect of a 22-minute HIIE session composed of 30-second sprints on subsequent food intake in 10-year-old lean children [17]. According to their results, food intake and macronutrient preferences at the following meal were not affected, which is consistent with previous results from our teams showing that only overweight and obese youth modify their food consumption after an intensive bout of exercise [7].

The aim of the present study was to examine the effect of a single HIIE session on subsequent energy intake, macronutrient consumption, appetite sensations and food reward in adolescents with obesity. Secondly, we questioned whether these post-exercise nutritional adaptations could be influenced by the degree of obesity in adolescents.

Methods

Population

Thirty three adolescents with obesity (according to Cole et al. [18]) aged 12-15 years old (Tanner stage 3-4) participated in this study (12 boys and 21 girls). The adolescents were recruited through the local Pediatric Obesity Center (Tza Nou, La Bourboule, France). The adolescents and their parents were proposed to participate by the pediatrician during their regular medical visit in the center. To be included in the study, participants had to be free of any medication that could interact with the protocol (e.g. diabetic or blood pressure medications), should not present any contraindications to physical activity, and had to take part in less than 2 hours of physical activity per week (according to the International Physical Activity Questionnaire –IPAQ [19]). This study was conducted in accordance with the Helsinki declaration and all the adolescents and their legal representative received information sheets and signed up consent forms as requested by the local ethical authorities (Human Ethical Committee (CPP Sud Est VI) authorization reference: AU 1178 2015).

Design

After a preliminary medical inclusion visit made by a pediatrician to control for the ability of the adolescents to complete the study, they were asked to perform a maximal aerobic test and their body composition was assessed by Dual-energy X-ray Absorptiometry (DXA). The adolescents were then asked to complete a food preference questionnaire and the Three-Factor-Eating-Questionnaire R21 [20] in order to exclude children with high cognitive restraint. Afterward, adolescents were randomly assigned to one of two experimental sessions performed one week apart: i) a rest condition without exercise (CON); ii) a High Intensity Interval Exercise condition (HIIE). On the two occasions, participants received a standardized breakfast (08:30) and started one of the two experimental conditions at 11:15 am (rest or exercise). Thirty minutes after the end of the experimental conditions (rest or exercise), participants had to complete the Leeds Food Preference Questionnaire (LFPQ) [21] before being served with an *ad libitum* buffet-style meal. They had to complete the LFPQ once more after the meal. Dinner energy intake was also assessed using an *ad libitum* buffet-style meal. Their appetite sensations were assessed at regular intervals through the day. Outside the experimental conditions and between the two *ad libitum* test meals, the adolescents were requested not to engage in any moderate to vigorous physical activity and mainly completed sedentary activities such as reading, homework or board games.

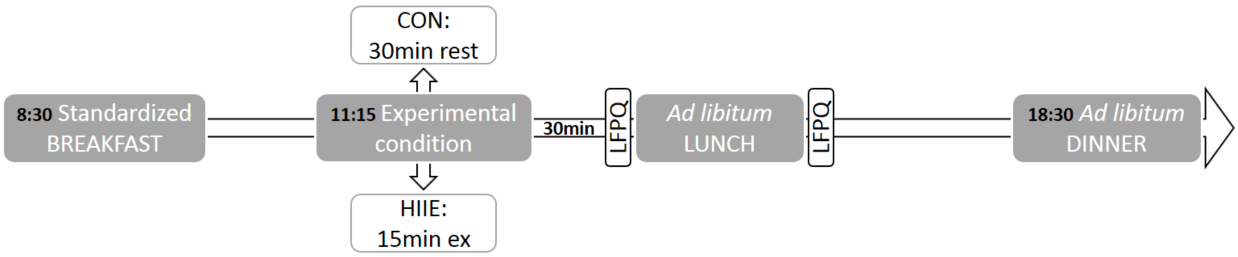

Figure 1. Design of the experimental days. CON: rest condition; HIIE: high intensity interval exercise; LFPQ: Leeds Food Preferences Questionnaire.

Anthropometric characteristics and body composition

Adolescents were weighed and had height measured wearing light clothing while bare-footed, using respectively a digital scale and a standard wall-mounted stadiometer. Body Mass Index (BMI) was calculated as weight (kg) divided by height squared (m^2). Afterwards, BMI was calculated in the sex and age dependent French reference curves to obtain the BMI percentile [22]. Fat mass (FM) and fat-free mass (FFM) were assessed by dual-energy X-ray absorptiometry (DXA) following standardized procedures (QDR4500A scanner, Hologic, Waltham, MA, USA). These measurements were obtained during the preliminary visit by a trained technician.

Maximal oxygen uptake test (VO_2)

Each subject performed a VO_2peak test on a traditional concentric ergometer [23]. The initial power was set at 30W during 3 minutes, followed by a 15W increment every minute until exhaustion. The adolescents were strongly encouraged by the experimenters throughout the test to perform their maximal effort. Maximal criteria were: heart rate >90% of the theoretical maximum heart rate (210 − 0.65 × age), Respiratory Exchange Ratio (RER = VCO2/VO2) > 1.1 and/or VO2 plateau. Cardiac electrical activity (Ultima SeriesTM, Saint Paul, MN) and heart rate (Polar V800) were monitored and the test was coupled with a measurement of gas exchanges breath by breath (BreezeSuite Software, Saint Paul, MN), that determined VO2 and CO2 (Carbon Dioxide) production (VCO2).

Volumes and gases were calibrated before each test. The VO2peak was defined as the average of the last 30 s of exercise before exhaustion.

Experimental conditions

Rest condition (CON): between 11:15 to 11:45 am, the participants remained seated on a comfortable chair (30 minutes). They were not allowed to talk, read, watch TV or to complete any intellectual tasks.

Exercise condition (HIIE): between 11:15 to 11:45 am, the participants were invited to perform a High Intensity Interval Exercise on an ergo-cycle, for a total duration of 15 minutes. Warming-up began at 60% of Maximal Heart Rate (HRmax) for 3 minutes. Then, adolescents had to perform 5 times the same pattern: 2 minutes intense bouts interspersed by active 30 seconds low intensity cycling. The intensity of the steps was as follows: 70%, 75%, 80%, 85%, and 90% HRmax. The intensity was controlled by heart rate records (Polar V800) using the results from the maximal aerobic capacity testing. Exercise induced energy expenditure was estimated afterwards based on the results obtained during the maximal oxygen uptake evaluation.

Perceived exertion

Immediately after exercise (HIIE session), the adolescents were asked to rate their perceived exertion using the Children's Effort Rating Table (CERT) from Williams et al. [24]. This scale was elaborated using a range of items from 1 to 10, the number 1 corresponding to an extremely easy exercise, while an effort leading the subject to interrupt the test because of its hard difficulty is indicated by 10.

Energy intake

At 08:00am, the adolescents consumed a standardized calibrated breakfast (500kcal) respecting the recommendations for their age (composition: bread, butter, marmalade, yoghurt or semi-skimmed milk, fruit or fruit juice). Lunch and dinner meals were served *ad libitum* using a buffet-type meal. The content of the buffets was determined based on the adolescent's food preferences and eating habits. Top rated items as well as disliked ones and items liked but not usually consumed were excluded to avoid over-, under- and occasional consumption. Lunch menu was beef steak, pasta, mustard, cheese, yogurt, compote, fruits and bread. Dinner menu was ham/turkey, beans, mashed potato, cheese, yogurt, compote, fruits and bread. Adolescents were told to eat until feeling comfortably satiated. Food items were presented in abundance. Food intake was weighted by the experimenters and the macro nutritive distribution (proportion of fat, carbohydrate and protein) as well as the total energy consumption in kcal were calculated using the software Bilnut 4.0. This methodology has been previously validated and published [25].

Subjective appetite sensations

Appetite sensations were collected throughout the day using visual analogue scales (150 millimeters scales) [26]. Adolescents had to report their hunger, fullness, desire to eat and prospective food consumption at 12 time points (before and immediately after breakfast, 30 minutes and 60 minutes after breakfast, prior and after the experimental condition (CON or HIIE), before and immediately after lunch, 30 minutes and 60 minutes after lunch, before and right after dinner). The questions were i) "How hungry do you feel?", ii) "How full do you feel?", iii) "Would you like to eat something?", iv) "How much do you think you can eat?".

Food liking and wanting

The Leeds Food Preference Questionnaire (described in greater methodological detail by Dalton and Finlayson [27]) provided measures of food preference and food reward. Participants were presented with an array of pictures of individual food items common in the diet. Foods in the array were chosen by the local research team from a validated database to be either predominantly high (>50% energy) or low (<20% energy) in fat but similar in familiarity, protein content, palatability and suitable for the study population. The LFPQ has been deployed in a range of research [27] including a recent exercise/appetite trial in young French males [28]. Explicit liking and explicit wanting were measured by participants rating the extent to which they like each food ("How pleasant would it be to taste this food now?") and want each food ("How much do you want to eat this food now ?"). The food images were presented individually, in a randomized order and participants make their ratings using a 100-mm VAS. Implicit wanting and relative food preference were assessed using a forced choice methodology in which the food images were paired so that every image from each of the four food types was compared to every other type over 96 trials (food pairs). Participants were instructed to respond as quickly and accurately as they could to indicate the food they want to eat the most at that time ("Which food do you most want to eat now?"). To measure implicit wanting, reaction times for all responses were covertly recorded and used to compute mean response times for each food type after adjusting for frequency of selection. Responses on the LFPQ were used to compute mean scores for high fat, low fat, sweet or savoury food types (and different fat-taste combinations).

Statistical analysis

Sample size was determined according to previous works reported in literature [11] and to an estimation based on effect-size difference greater than 0.6, for a two-sided type I error at 5%, a statistical power at 90% and a correlation coefficient at 0.5 (two conditions for a same subject). For these assumptions, 32 subjects were enough to detect such true difference between the two conditions where our recruitment enrolled 33 subjects. Statistical analysis was performed using Stata software (version 13; StataCorp, College Station, Texas, USA) and Statview (version 4 for Windows). Continuous data were expressed as mean (± standard deviation (SD)). All tests were two-sided, with a Type I error set at 0.05. The normality of the data was checked using the Smirnov-Kolmogorov test. Adapted paired T-tests were used to compare absolute and relative energy intake, macronutrient preferences and energy expenditure between conditions (CON and HIIE). For appetite sensations, area under the curves (AUC, based on the trapezoid methods) were calculated and compared between CON and HIIE using T-test. To measure the *ad* *libitum* meal effect on relative preference, implicit wanting, explicit wanting and explicit liking, statistical analysis was conducted with linear mixed models to take into account the repeated measurements per subject. Interaction between time (before and after meal) and condition (CON and HIIE) was tested before performing subgroup analyzes. Our sub-analysis, questioning the effect of degree of obesity, children were classified in tertiles (based on weight, BMI, FM% and FFM kg as the main anthropometric and body composition indicators used in the literature to characterize obesity). One-way ANOVA were used to compare lunch energy intake, macronutrient preferences, and appetite sensations AUC on CON and HIIE between tertiles. Bonferroni post-hoc test were used when appropriate.).

Results

Characteristics of the participants

Thirty-three healthy adolescents with obesity were recruited for this study (11 boys, 21 girls). Participants had an average (± SD) age of 13.3 (± 0.9) years; weight: 93.2 (± 13.0) kg; BMI: 35.0 (± 4.3) kg/m^2; z-BMI: 2.3 (± 0.2); fat mass: 37.6 (± 3.5)%; fat free mass: 55.9 (± 7.3) kg and VO_2peak: 23.5 (± 4.3) ml/min/kg.

Characteristics of HIIE and CON condition

Energy expenditure (EE) induced by exercise (total duration 15 minutes) was significantly higher compared to the 30-minute resting energy expenditure (respectively 102 (± 21) kcal; and 52 (± 10) kcal; $p<0.001$). The rate of perceived exertion by the end of the HIIE was 5.8 (± 2.0).

Energy intake

Absolute energy intake (EI) at lunch (HIIE: 1102 (± 276) kcal and CON: 1222 (± 310) kcal; $p=0.014$; which represents a difference of 7%), as well as the total energy intake over the day (HIIE: 2062 (± 460) kcal and CON: 2177 (± 471) kcal; $p=0.044$; which represents 4%

difference) were significantly lower on HIIE compared with CON. Moreover, relative energy intake after lunchtime (REI = EI-EE) was also lower on HIIE compared with CON (1005 (± 274) kcal and 1172 (± 306) kcal respectively; p=0.001) (Table1).

Macronutrient consumption

The macronutrient intake expressed as both absolute intake (grams) and percentage of the total ingested energy, is shown in Table2. On HIIE, the adolescents consumed significantly less protein and fat (in grams) at lunch compared to CON (p=0.008 and p=0.022). This difference is still significant regarding the total protein and fat content of the food consumed all day (p=0.020 and p=0.033). The carbohydrate consumption at lunch tended to decrease on HIIE compared with CON (p=0.058).

Table 1. Energy expenditure, energy intake and relative energy intake, in response to high intensity interval exercise (HIIE condition) or rest (CON condition), in obese adolescents.

	CON Mean (± SD)	**HIIE Mean (± SD)**	***p* value**
Lunch EI (kcal)	1222 (± 310)	1102 (± 276)	0.014
Lunch REI (kcal)	1172(± 306)	1005 (± 274)	0.001
Dinner EI (kcal)	955 (± 228)	960 (± 246)	0.877
Total EI (kcal)	2177 (± 471)	2062 (± 460)	0.044

CON: control condition; HIIE: high intensity interval exercise; EI: energy intake; REI: relative energy intake (EI-EE); SD: Standard Deviation; *: p<0.05; **: p<0.01; ***: p<0.001, NS: not significant

Table 2. Absolute (grams) and relative (percentages) macronutrient consumption between meals during each experimental condition.

	CON		HIIE		*p* value	
	Grams Mean (± SD)	% Mean (± SD)	Grams Mean (± SD)	% Mean (± SD)	Grams	%
Lunch protein	64.3 (± 13.0)	21.4 (±2.3)	58.6 (± 13.0)	21.5 (± 2.5)	0.008	0.801
Dinner protein	57.1 (± 15.8)	24.3 (± 6.2)	56.5 (± 14.5)	24.3 (± 6.2)	0.782	0.948
Total protein	121.4 (± 22.9)	22.6 (± 3.4)	115.1 (± 23.1)	22.7 (± 3.3)	0.020	0.994
Lunch fat	45.6 (± 9.6)	34.7 (± 8.6)	41.6 (± 9.8)	34.6 (± 6.0)	0.022	0.947
Dinner fat	33.5 (± 18.7)	30.2 (± 12.1)	32.0 (± 17.8)	28.3 (± 11.0)	0.430	0.120
Total fat	79.5 (± 22.5)	32.7 (± 6.1)	73.6 (± 22.7)	31.9 (± 5.9)	0.033	0.384
Lunch CHO	139.6 (± 54.8)	44.5 (± 8.0)	124.7 (± 47.5)	44.4 (± 8.9)	0.058	0.947
Dinner CHO	107.9 (± 29.4)	46.2 (± 11.7)	113.0 (± 29.9)	48.0 (± 9.9)	0.376	0.265
Total CHO	247.5 (± 70.7)	45.3 (± 7.1)	237.8 (± 66.7)	46.1 (± 7.0)	0.308	0.499

CON: control condition; HIIE: high intensity interval exercise; CHO: Carbohydrate; NS: not significant; SD: Standard Deviation

Subjective appetite sensations

Overall daily hunger, satiety, desire to eat and prospective food consumption were not different between conditions as illustrated by Figure2.

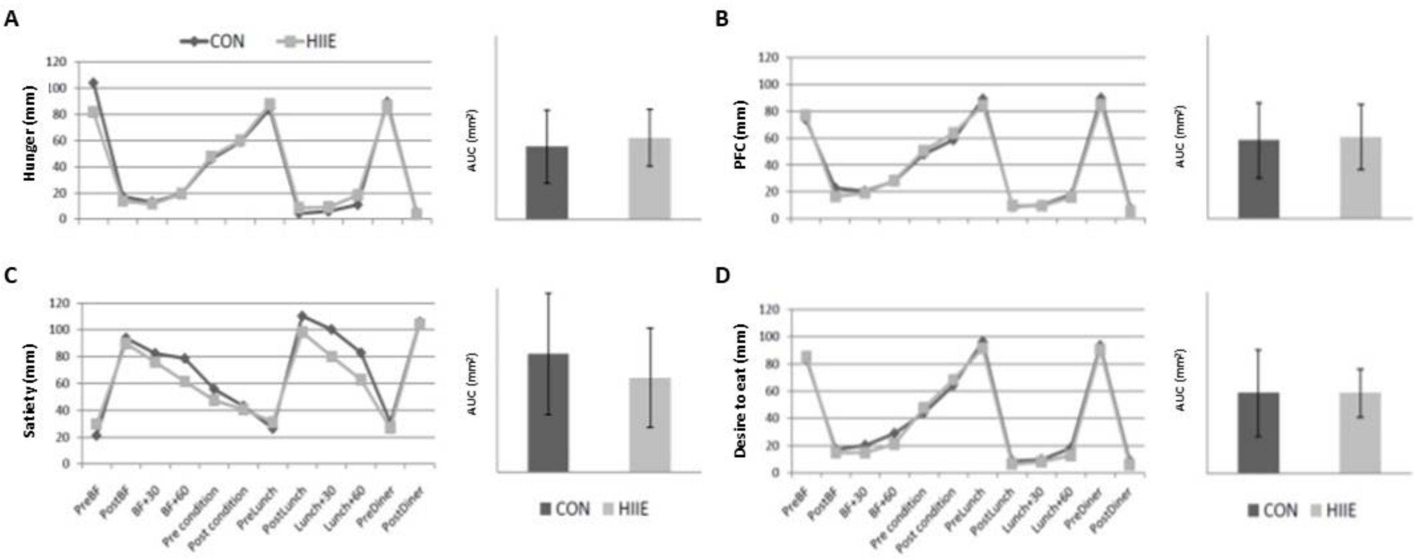

Figure 2. Subjective Hunger **(A)** Satiety **(B)** Prospective Food Consumption **(C)** and Desire to Eat **(D)** kinetics (left side) and Area Under the Curve (AUC, right side). CON: rest condition; HIIE: high intensity interval exercise; AUC: area under the curves.

Food reward

Our results show a significant meal x condition interaction for taste implicit wanting (p=0.046) with sweet taste implicit wanting increasing after the *ad libitum* meal on CON while decreasing on HIIE (see Table3: a positive score for fat and/or taste biais indicates a preference for high fat and/or sweet food; a negative score for fat and/or taste biais indicates a preference for low fat and/or savoury food). The before meal LFPQ results were not different after the rest or the HIIE condition. However, whereas no meal effect on CON was observed; fat relative preference, sweet taste relative preference and fat implicit wanting significantly decrease in response to the *ad libitum* meal on HIIE (p=0.026, p=0.013 and p=0.010 respectively).

Table 3. Relative preference, implicit wanting, explicit wanting and explicit liking for high *vs* low fat foods and sweet *vs* savory foods, between rest and exercise condition.

			CON Mean (± SD)	**Time**	**HIIE Mean (± SD)**	**Time**	**Condition**	**Interaction time * condition**
Relative preference	Fat bias	Before	4.1 (± 9.7)	0.101	3.3 (± 9.5)	0.026	0.729	0.814
		After	1.2 (± 8.2)		0.1 (± 8.0)			
	Taste bias	Before	-3.9 (± 13.3)	0.839	-0.8 (± 13.9)	0.013	0.217	0.092
		After	-3.2 (± 10.9)		-5.0 (± 11.8)			
Implicit wanting	Fat bias	Before	7.7 (± 28.3)	0.535	22.3 (± 55.7)	0.010	0.157	0.093
		After	1.2 (± 51.2)		-13.2 (± 58.5)			
	Taste bias	Before	-15.0 (± 42.9)	0.076	-5.7 (± 70.6)	0.203	0.660	0.046
		After	5.1 (± 60.8)		-22.6 (± 50.3)			
Explicit wanting	Fat bias	Before	6.2 (± 12.1)	0.238	3.5 (± 15.5)	0.932	0.245	0.461
		After	3.2 (± 9.7)		3.1 (± 12.3)			
	Taste bias	Before	-4.1 (± 12.8)	0.688	-1.7 (± 16.4)	0.304	0.472	0.693
		After	-5.4 (± 14.7)		-4.8 (± 11.1)			
Explicit liking	Fat bias	Before	5.0 (± 12.6)	0.104	4.7 (± 14.7)	0.569	0.863	0.472
		After	1.4 (± 10.3)		3.5 (± 12.5)			
	Taste bias	Before	-6.3 (± 12.0)	0.857	-2.2 (± 13.6)	0.174	0.070	0.288
		After	-5.5 (± 15.4)		-5.5 (± 11.8)			

CON: control session; HIIE: high intensity interval exercise; NS: not significant; SD: Standard Deviation

Effects of the degree of obesity

As detailed in the statistical analysis section, adolescents were classified in tertiles, depending on their degree obesity, according to four categories: weight, BMI, FM% and FFM (Table4).

Regarding lunch energy intake depending of the degree of obesity, the delta between HIIE and CON was significantly different between the first and third BMI tertiles (ANOVA p=0.013; post-hoc T1 *vs* T3 p=0.004): a 21% lower energy intake (-287 (± 242) kcal) was observed after HIIE compared with CON in adolescents within the third BMI tertile, while those in the first one (then with a lower BMI) increased their food consumption at the lunch test meal by 8% (+33 (± 284) kcal) in response to HIIE. Similar results were observed when using FM% tertiles (ANOVA p=0.033), where lunch food intake was lower in response to the HIIE session in the adolescents of the second and third FM% tertiles only (-15% (-219 (± 283) kcal) for the third FM% tertile and -14% (-189 (± 222) kcal) for the second FM% tertile), while an 8% (+45 (± 225) kcal) increase was observed in the first FM% tertile (T1 *vs* T2: p=0.033; T1 *vs*. T3: p=0.017). The results are illustrated in Figure3.

The macronutrient consumption depending on the tertiles of obesity showed a significant BMI tertiles x conditions interaction on carbohydrate consumption (in grams) (p=0.015): while the first BMI tertile (lower BMI) increased CHO consumption after HIIE compared to CON (+8g), the second and the third BMI tertiles decreased their intake of CHO (-13.2g and -41.4g). For the sensations of appetite, we did not find either any difference between tertiles.

Table 4. Description of the obesity tertiles.

	T1 Mean (± SD)	T2 Mean (± SD)	T3 Mean (± SD)	*ANOVA*	*Post-hoc*
Weight tertiles	81.00 (± 3.63)	90.48 (± 3.12)	107.13 (± 12.53)	<0.001	T1<T2*; T1<T3*** T2<T3***
BMI tertiles	30.69 (± 1.52)	34.78 (± 0.66)	39.42 (± 3.95)	<0.001	T1<T2<T3***
FM % tertiles	33.65 (± 1.79)	38.01 (± 1.16)	41.13 (± 2.10)	<0.001	T1<T2<T3***
FFM kg tertiles	48.84 (± 2.11)	54.75 (± 1.73)	64.26 (± 5.42)	<0.001	T1<T2<T3***

T1: first tertile; T2: second tertile; T3: third tertile; BMI: Body Mass Index; FM: Fat Mass; FFM; Fat Free Mass; SD: Standard Deviation; *: p=0.015; ***: p<0.001.

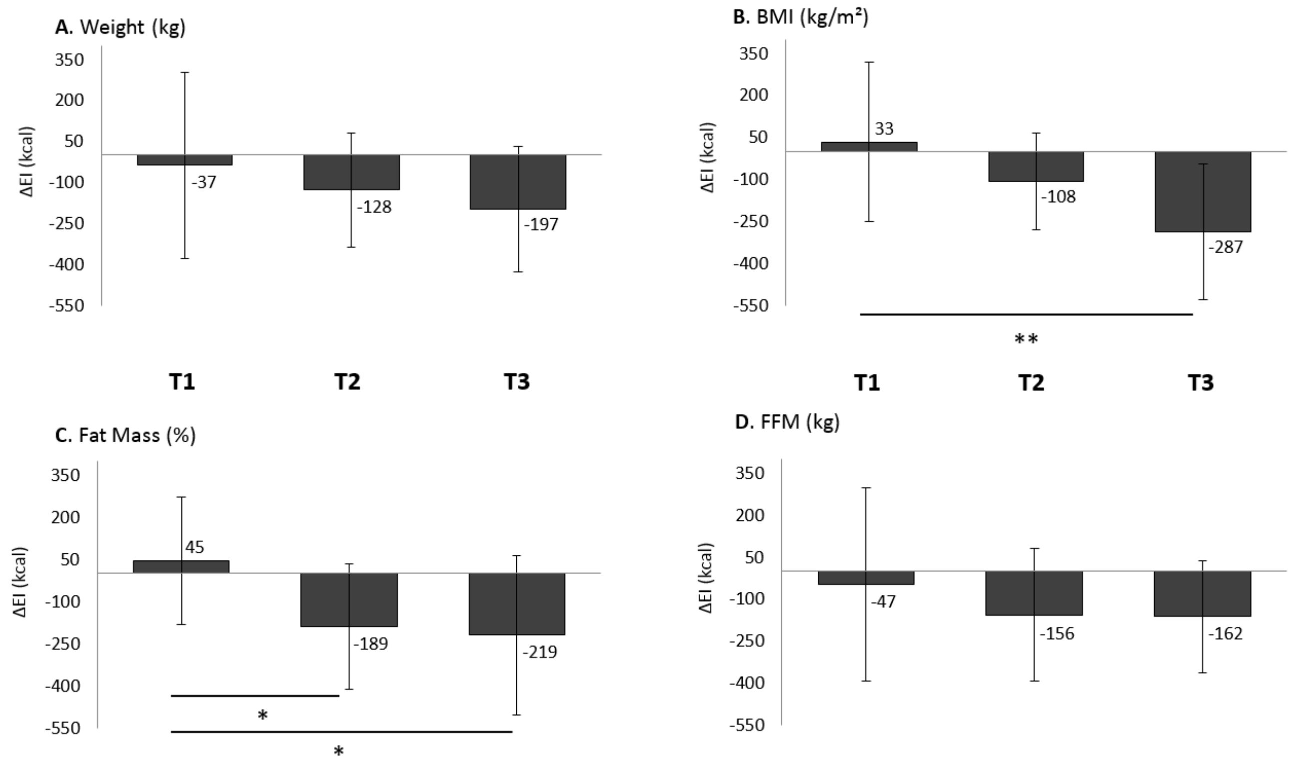

Figure 3. Lunch energy intake differences (ΔEI) in response to high intensity interval exercise compare to control session, related to weight **(A)**, body mass index **(B)**, fat mass **(C)** and fat free mass **(D)** tertiles. Δ EI: Energy intake difference between control and high intensity interval exercise session; T1: first tertile; T2: second tertile; T3: third tertile; BMI: Body Mass Index; FM: Fat Mass; FFM; Fat Free Mass; SD: Standard Deviation; *: p<0.05; **: p<0.01

Discussion

While HIIE is largely promoted as an efficient anti-obesity strategy thanks to its beneficial effects on body composition and cardio-metabolic health [14], less is known regarding its potential nutritional impacts. The present study examined for the first time the effect of a single HIIE session on subsequent energy intake, macronutrient consumption, appetite sensations and food reward in adolescents with obesity. According to our main result, an acute HIIE session reduced subsequent *ad libitum* food intake (at the following test meal and whole day), despite unchanged appetite feelings in 12-15 years old patients with obesity. HIIE was also found to decrease post *ad libitum* meal food reward in adolescents with obesity. Interestingly these nutritional responses seem to depend on the adolescents' degree of obesity.

Recently, Morris and collaborators explored for the first time the effects of HIIE on food consumption and appetite sensations in children [17]. Contrary to our results, their 22-minutes HIIE session composed of 30-second sprints did not affect subsequent food intake in lean children [17]. Altogether, Morris et al. and our results confirm the actual literature clearly showing that intensive acute exercise can favor reduced energy intake in overweight and obese but not lean children and adolescents [7], [9], [11], [29]. These results add to the available evidence and suggest that HIIE might not only have beneficial effects on body composition, physical and cardio-metabolic fitness, but can also favor a transient negative energy balance, as illustrated by the significantly lower REI observed in the present work, as compared with a rest session. Importantly, this is accompanied by a low rate of perceived exertion, highlighting the acceptability and feasibility of such exercise modality in youth with obesity. While further chronic studies are needed to test the nutritional responses to long term High Intensity Interval Training, the observed transient anorexigenic effect of HIIE can be explained by some physiological and neurocognitive responses. Indeed, as already expressed in the literature, HIIE affects the concentrations of some of the main appetite-related peptides in adolescents with obesity, favoring increased PYY3-36 [30] and decreased active ghrelin [9]. Recent data suggest that post-intensive exercise energy intake modifications can also be explained by the response to exercise of some neural networks involved in the cognitive processing of food-related cues. In their work, Fearnbach et al. recently questioned the potential role played by such cognitive processing of food-related cues in the nutritional response to exercise in children and adolescents [13], [31]. Their results showed that the neural response reflecting the cognitive effort engaged in response to food stimuli is significantly reduced compared to non-food ones after a 45-minute cycling exercise set at moderate-to-high intensity in obese, but not lean adolescent boys [13], [31]. Importantly, this reduced neural activation was accompanied by a significant decreased energy intake at the following meal compared to a rest condition [31].

While all the previously published studies in the field have considered weight status, the present analysis also questioned whether the degree of obesity may influence the adolescents' post-exercise energy intake. According to this sub-analysis, the transient anorexigenic effect of exercise seems to be stronger in adolescents with higher BMI and higher fat mass percentage. Indeed, a 21% decreased energy intake was observed after HIIE compared with CON in adolescents within the third BMI tertile, while those in the first one (with a lower BMI) increased their food consumption at the test meal by 8% in response to HIIE. Similar results were observed when using FM% tertiles, where food intake was reduced in response to the HIIE session in the adolescents of the second and third tertiles only (-15% for the third tertile and -14% for the second one), while a 8% increase was observed in the first tertile. These results are consistent with previous works done by Fearnbach et al. who found body composition specific post-exercise neural responses to food cues [13], [32]. According to their results, body weight, BMI and FM are inversely correlated with the neural response to food stimuli following exercising [13]. In other words, they found that a higher index of adiposity was associated with lower brain responsiveness to food stimuli following 45 minutes-cycling exercise (at 65% VO_2max). Thus, our results indicating a body composition specific nutritional post-exercise response may be explained by different cognitive processing of food stimuli: the greater post-exercise reduced energy intake in adolescents with the highest degree of obesity could be explained by a reduced neural response to food cues. Our results however failed to show any significant difference between FFM tertiles, which seems contradictory with the actual literature pointing a strong association between lean mass and daily energy intake in both adults and adolescents [33], [34] with Fearnbach et al. moreover showing a positive association between fat-free mass index and post-exercise intake in children at risk for obesity [35].

Interestingly, the reduced food consumption observed in the present work is not due to a particular effect on one specific macronutrient. Indeed, absolute protein, fat and CHO intakes at the test meal were all reduced (tendency for CHO) with no change of their respective contribution to the total energy ingested. Although the literature remains quite divergent regarding the macronutrient response to acute exercise, these results are in line with a recent systematic review suggesting that children and adolescents with obesity do not alter their relative macronutrient composition in response to acute exercise and calling for further specific researches [7]. Our secondary analysis however showed a significant BMI tertiles x CHO consumption interaction, with a higher CHO intake by the adolescents with lower BMI after HIIE while the adolescents of the second and the third BMI tertiles decreased their CHO consumption. More studies are needed regarding the potential effect of body composition on post-exercise macronutrient consumption.

Importantly, the observed post-exercise reduction in energy intake was not accompanied by any change in subjective appetite sensations (feelings of hunger, satiety, prospective food consumption or desire to eat); suggesting that this effect occurs without any food frustration in adolescents. This result is in line with previous works that have already highlighted this uncoupling effect of exercise on energy intake and appetite sensations in children and adolescents [36].

Elsewhere, evidence indicates that exercise may be link to food intake through its potential effect on food reward. If previous works have demonstrated the effect of exercise on explicit and implicit hedonic process in adults [15], [16], [37], [38], the present work is the first to question the effect of acute exercise on food reward in adolescents with obesity. According to our results, implicit wanting for sweet taste decreased in response to the *ad libitum* meal during the HIIE condition, while it increased after the CON condition. Furthermore, the preferences for high fat foods and sweet foods (relative to low fat foods and savory foods) were significantly reduced in response to our *ad libitum* test meal after the acute HIIE condition but not during the rest condition. Similarly, HIIE favored a reduced fat implicit wanting after the *ad libitum* meal compared to the rest condition. Altogether, these results suggest that an acute bout of HIIE might favor reduced reward for fat and sweet foods. These results are in line with previous works that demonstrated that food reward is altered by both aerobic and resistance acute exercises [38]. Indeed, McNeil et al. found greater relative preference for high fat as well as greater explicit wanting for high fat during their CON condition compared to both (aerobic and resistance) exercises. However, Finlayson et al. highlighted high inter-individual food hedonic responses to exercise showing that while some individuals decreased their desire to eat after exercising others increased their implicit wanting [37]. Further studies considering and questioning the inter-individual variability regarding post-exercise food reward are needed in both adults and youth.

The present results have to be interpreted in light of some limitations. First, although our results provide new interesting insights regarding the post-exercise energetic and behavioral adaptations of appetite control, physiological and neurocognitive investigations are missing to provide some potential explanatory mechanisms. Moreover, while acute exercises, particularly intensive ones, have be shown to impact energy balance (intake and expenditure) for up to 72 hours, it would have been useful to assess energy expenditure and intake for the following days. Although the fact that the rest and the exercise conditions are not of exact same duration could be considered as a limitation of the study, the standardization of the timing between the end of both experimental conditions and the LFPQ and *ad libitum* meal (30 minutes after both) has to be highlighted (so that the delay between the experimental conditions and the nutritional evaluations was the same). Furthermore, these results relate to the acute effect of HIIE on appetite control in adolescents with obesity; however, longitudinal investigations should be conducted, since it has been suggested in adults with obesity that four weeks of high intensity interval training might minimize the enhancement of food reward compared with a moderate intensity interval training [16]. Similarly, it must be underlined that our secondary analysis, questioning the effect of the degree of obesity using tertiles, might have been influenced by the fact that all the adolescents received the same breakfast independently of their level of obesity and then basal energy needs, which might have influenced energy intake at the test meal. Importantly, our analysis did not show gender differences, which is in line with previously published studies that have already pointed this absence of gender effect regarding post-exercise energy intake and appetite feelings in adolescents with obesity [39].

Conclusion

In conclusion, the present study found that an acute session of HIIE favors reduced subsequent energy intake and food reward despite unchanged appetite feelings in adolescents with obesity. Although this joins up with the actual literature regarding the effect of intensive exercise on subsequent nutritional responses in obese youth, our results seem to indicate for the first time that these nutritional responses depend on the adolescents' degree of obesity with a greater anorexigenic effect observed with higher obesity. Further studies are needed regarding the effects of HIIE on appetite and energy intake in such a population and to better understand this potential role played by the degree of obesity in adolescents.

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ÉTUDE IV :

Effet de 10 mois de prise en charge multidisciplinaire sur la prise alimentaire et le système de la récompense chez l'adolescent en situation d'obésité.

Weight loss induced by a 10-month inpatient multidisciplinary intervention may be associated with decreased in food reward in adolescents with obesity

Miguet Maud, Beaulieu Kristine, Fillon Alicia, Khammassi Marwa, Masurier Julie, Lambert Céline, Duclos Martine, Boirie Yves, Finlayson Graham, Thivel David

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Abstract

Background. While multidisciplinary weight loss programs - including physical activity - have been suggested to improve eating disorders, emotional eating, and the sensitivity of the appetite control system; this study examined the effect of a specific multidisciplinary intervention on appetite control and food reward in adolescents with obesity.

Methods. Thirty adolescents with obesity (11-15 years) took part in a 10-month inpatient multidisciplinary weight loss program. Body composition, energy intake, appetite, food reward and eating behavior traits were measured at baseline, 5 months and the end of the 10-month intervention.

Results. *Ad libitum* intake decreased after the 10-month intervention ($p<0.001$). Fasting hunger ($p=0.02$) and desire to eat ($p=0.01$), daily hunger ($p=0.001$) and pre-meal liking for high-fat savoury foods (HFSA; $p=0.03$), low-fat savoury foods (LFSA; $p=0.04$), high-fat sweet foods (HFSW; $p=0.009$), low-fat sweet foods (LFSW; $p=0.005$) increased after 5 months. Fasting and daily hunger ($p=0.02$ and $p=0.008$, respectively), desire to eat ($p<0.001$ and $p=0.005$, respectively), prospective food consumption (PFC; $p=0.048$ and $p=0.03$, respectively); pre-meal liking for HFSA ($p=0.007$), LFSA ($p<0.001$), HFSW ($p=0.02$), LFSW ($p<0.001$); emotional eating ($p<0.001$) and uncontrolled eating ($p=0.009$), decreased between months 5 and 10. Post-meal liking for HFSA ($p<0.001$), LFSA ($p=0.002$), HFSW ($p=0.02$) and LFSW ($p<0.001$) decreased between baseline and month 5 and remained unchanged between months 5 and 10.

Conclusion. These results indicate possible improvements in the reward response to food in adolescents with obesity and may contribute to the beneficial effect of a multicomponent weight loss intervention in this population. These findings suggest that adaptive mechanisms to weight loss occurring in the short-to-medium term are attenuated in the longer term with the persistence of weight loss.

Key words. Weight Loss, Multidisciplinary Intervention, Energy Intake, Food Reward

Introduction

In the current obesogenic environment, the interaction between the homeostatic and hedonic appetite systems in the control of energy intake is of considerable interest [1]. The increasing availability of highly palatable food is likely to favor overeating, independently of dietary status [2].

Adolescents are particularly vulnerable to increased consumption of unhealthy foods and rising obesity rates [3], with one out of five children having obesity in Europe [4]. During adolescence, consumption of 'junk food' or other high-fat foods is related to pleasure, social influence from peers and independence from parental control [5]. In that regard, the relationship between food reward and obesity has been previously demonstrated, with higher relative reinforcing value of food predicting greater weight gain [6], while lower food reinforcement is associated with better weight loss [7]. Since childhood is an important period to enhance food acceptance and induce a wider dietary range, research is needed to identify strategies to make children's food preferences and food choices healthier during this critical time. This is especially important because 80% of adolescents with obesity are at high risk of becoming adults with obesity [8].

Recently, physical activity has been described as a good strategy to decrease eating disorders, emotional eating and energy intake in adults and adolescents with obesity [9]–[12] as well as improving the sensitivity of the appetite control system in adults [13]. Moreover, a recent systematic review revealed that liking and wanting for high-energy dense food decreased following weight management interventions in adults [14], contrary to the notion that adaptive mechanisms may increase appetite and food reward to counteract weight loss. Such results suggest that the effect of physical activity and weight loss interventions on overall health, body weight and body composition might be in part mediated by modifications in eating behaviors. Physiological pathways have been identified to explain some of these nutritional responses to exercise [15]; however, the neurocognitive factors remain less explored. Specifically, food reward appears to be an important factor likely to be implicated in the success of weight loss programs, but this remains to be investigated.

Currently, weight management interventions tend to rest on multidisciplinary approaches involving nutritional counselling, psychological support and exercise [16]. Such interventions have been shown effective (at least in the short term), leading to significant improvements in body weight and body composition [17], physical fitness [17], cardio-metabolic profile [18], and health-related quality of life [19], among others. However, their effects on eating behaviors are mixed. Although a recent meta-analysis found reduced daily energy intake in response to multicomponent weight loss programs in adolescents with obesity [10], it also noted that most studies assessed energy intake as a secondary outcome using self-reported food diaries, which have been shown to favor underestimation of food consumption in this population [20]. The authors therefore expressly identified the need for additional studies using alternative dietary assessment strategies with less potential bias [10]. According to some recent results from our research group, adolescents with obesity significantly increased their weighed daily ad libitum energy intake in response to multidisciplinary weight loss interventions [21], [22]. Importantly, our work also highlighted the need to consider the adolescents' individual eating behavior traits, given that the most cognitively restrained eaters appeared to be the most vulnerable to increased energy intake in tempting situations [23], such as ad libitum buffet meals [21], [22]. The potential underlying mechanisms remain to be elucidated, particularly the potential effect of such weight loss intervention on the hedonic and cognitive control of food consumption.

The primary aim of this study was to investigate the homeostatic (energy and macronutrient intake and appetite sensations) and food reward (explicit liking and implicit wanting) responses to a 10-month multidisciplinary weight loss intervention among youths with obesity. The secondary aims were to examine the effects of the intervention on cognitive control over eating (eating behaviour traits).

Methods

Participants

A total of 30 adolescents (mean age: 13.1 ± 1.0 years) with obesity as defined by Cole et al. [24] (mean BMI z-score: 2.3 ± 0.2; BMI percentile: 98.7 ± 0.5) were enrolled in this study (7 boys and 23 girls) through local pediatric consultations. Convenience sampling was used in this study. To be included, the adolescents had to: i) be aged between 11 and 15 years; ii) present a BMI equal or above the 95th percentile for their gender and age [24]; iii) not take any medication that could interact with the protocol (e.g., thyroid medication, stimulant medication, medication for diabetes); iv) present no contraindication to physical activity; and v) take part in less than 2 hours of physical activity per week (according to the International Physical Activity Questionnaire – IPAQ). All the adolescents and their legal representative received information sheets and signed up consent forms as requested by the ethical authorities.

Protocol design

After a medical screening conducted by a pediatrician to ensure their ability to complete the study, the adolescents were enrolled in a 10-month residential multidisciplinary weight loss program in a local Pediatric Obesity Center (Tza Nou, La Bourboule, France). Maturation status was assessed by the physician using the Tanner stages during the first medical visit. Anthropometric measurements, body composition (dual-energy X-ray absorptiometry), daily energy intake (ad libitum buffet meals), food reward (Leeds Food Questionnaire Preference), eating behavior traits (Three-Factor Eating Questionnaire) and appetite sensations (visual analogue scales) were assessed before (T0), after 5 months (T1), and at the end of the 10-month program (T2). This study was conducted in accordance with the Helsinki declaration and received ethical approval (CPP Sud Est VI: 2015-33; Clinical Trial NCT02626273).

Measurements

The following measurements were performed at baseline (T0), 5 months (T1) and the end of the 10-month program (T2).

Anthropometric characteristics and body composition

Body weight and height were recorded to the nearest 0.1 kg and 0.5 cm, respectively, while wearing light clothes and bare-footed, using a digital scale and a standard wall-mounted stadiometer, respectively. BMI was calculated as weight (kg) divided by height squared (m^2). Afterwards, BMI was reported in the sex and age dependent French reference curves to get the BMI percentile. Fat mass (FM) and fat-free mass (FFM) were assessed, under fasted state, by dual-energy X-ray absorptiometry (DXA) following standardized procedures (QDR4500A scanner, Hologic, Waltham, MA, USA).

Eating behavior traits

The Three-Factor Eating Questionnaire (TFEQ R-21; Cappelleri et al. 2009) was used to assess eating behavior traits. Three domains were evaluated: uncontrolled eating (UE: tendency to overeating in response to loss of control over intake); emotional eating (EE: overeating in response to negative moods) and cognitive restraint (CR: individuals' efforts to limit their food intake to control body weight or to promote weight loss). Participants completed the 21 items in a four-point Likert scale for items 1–20 and on an eight-point numerical rating scale for item 21. Their answers were coded following the instructions given by Cappelleri et al. [27]. Items 1 to 16 were reverse coded and item 21 was recoded as follows: 1–2 scores as 1; 3–4 as 2; 5–6 as 3; 7–8 as 4. Means for each domain were then calculated (domain score also range from 1 to 4), with higher score indicate more UE, EE and CR.

Ad libitum energy intake

Daily ad libitum energy intake was assessed during three single test days performed at T0, T1 and T2. At 08:00, after an overnight fast, the adolescents consumed a standardized calibrated breakfast respecting the recommendations for their age (≈500 kcal, [26]. Lunch (12 p.m.) and dinner (6:30 p.m.) meals were ad libitum served using a buffet-type meal. The content of the buffets was determined based on the adolescent's food preferences and eating habits. Top rated items as well as disliked ones and items liked but not usually consumed were excluded to avoid over-, under- and occasional/opportunistic consumption. At lunch, the menu was composed of beef steaks, pasta, mustard, cheese, yogurt, apple sauce, fruits and bread. Dinner menu was composed of ham/turkey, beans, mashed potatoes, cheese, yogurt, apple sauce, fruits and bread. Food items were presented in abundance and accompanied with water (1-L carafe) only. Adolescents made their choices and composed their trays individually before joining their habitual table (5 adolescents per table). Adolescents were told to eat until feeling comfortably satiated and had access to extra food if wanted. Food items were weighed by the experimenters before and after consumption, and the macronutrient distribution (proportion of fat, carbohydrate and protein) and total energy intake in kcal were calculated using the software Bilnut 4.0 (4.0 SCDA, Nutrisoft, Software, France). Total daily energy intake was calculated by summing breakfast, lunch and dinner meals. This methodology has been previously validated and published [27]. Between the test meals, the adolescents did not have access to any food but were free to drink water ad libitum, and were requested not to engage in any moderate to vigorous physical activity and mainly performed sedentary activities such as reading, homework, or board games.

Subjective appetite sensations

Appetite sensations were collected throughout the test day using visual analogue scales (150-mm scales). Adolescents reported hunger, fullness, desire to eat and prospective food consumption at six regulated times: before and immediately after the breakfast, lunch, and dinner. The questions were: i) "How hungry do you feel?", ii) "How full do you feel?", iii) "Would you like to eat something?", iv) "How much do you think you can eat?" (Adolescents were asked to respond on a scale from "not at all" to "a lot"). This method has been previously validated [30]. Area under the curve (AUC) was calculated based on the trapezoid method for daily appetite sensations.

Food liking and wanting

The reward value of food was assessed pre-lunch (hungry state) and post-lunch (fed state) during the test days. The Leeds Food Preference Questionnaire (described in greater methodological detail by Dalton and Finlayson [29] provided measures of food preference and food reward. Participants were presented with an array of pictures of individual food items common in the diet. Foods in the array were chosen by the local research team from a validated database to be either predominantly high (>50% energy) or low (<20% energy) in fat but similar in familiarity, protein content, palatability and suitable for the study population. Explicit liking was measured by participants rating the extent to which they like each food ("How pleasant would it be to taste this food now?"). The food images were presented individually, in a randomized order and participants make their ratings using a 100-mm VAS. Implicit wanting was assessed using a forced choice methodology in which the food images were paired so that every image from each of the four food types was compared to every other type over 96 trials (food pairs). Participants were instructed to respond as quickly and accurately as they could to indicate the food they want to eat the most at that time ("Which food do you most want to eat now?"). To measure implicit wanting, reaction times for all responses were covertly recorded and used to compute mean response times for each food type after adjusting for frequency of selection. Responses on the LFPQ were used to compute mean scores for high fat, low fat, sweet or savoury food types (and different fat-taste combinations).

Multidisciplinary weight loss program

The 10-month residential multidisciplinary weight loss program combined physical activity, nutritional education and psychological support. The physical activity intervention was composed of four 60-minute physical activity sessions per week including aerobic training, strength training, aquatic activities and leisure-time activities (e.g. soccer). Concomitantly, the adolescents attended 2 hours of physical education per week at school. The adolescents also attended nutritional education classes twice a month led by a dietician and received psychological support through individualized consultations with a professional once a month. During the intervention, the adolescents were prescribed a balanced diet, based on their age and sex recommendations for energy requirements in accordance with the national nutrition guidelines [30]. Adolescents were not subjected to energy restriction. The focus of the nutritional intervention was on the regularity of the meal, the variety and the quality of the food [31].

Statistical analyses

Statistical analysis was performed using Stata software (version 13; StataCorp, College Station, Texas, USA). All tests were two-sided, with a Type I error set at 0.05. As discussed by Feise in 2002, the adjustment of Type I error were not proposed systematically but according to clinical and not only statistical considerations [32]. Continuous data were expressed as mean and standard deviation. To measure the effect of the 10-month intervention over time (T0, T1, and T2) on weight, BMI, FM, FFM, EI, macronutrients, appetite sensations, eating behaviors scores, statistical analyses were conducted with linear mixed models to take into account the repeated measurements per subject (time as fixed effect and subject as random effect). Paired t-tests were used to compare changes during phase 1 and phase 2. To measure the meal effect (before/after meal) on food reward, linear mixed models were also considered at each time, with meal (before/after meal) as fixed effect and subject as random effect. Interaction between time (T0, T1, and T2) and meal (before/after meal) was tested before performing subgroup analyses.

Results

Participant characteristics

Among the initial 30 children included, 24 completed the 10-month intervention (80% retention). Of the six participants who left the trial, two were excluded for disciplinary reasons, three discontinued the intervention for family reasons and one for school-related reasons. None of the dropouts was related to the study protocol.

Anthropometric and body composition changes are presented in Table 1. As expected, body weight, body mass index and percent fat mass decreased significantly throughout the 10-month weight loss intervention ($p<0.001$). There was also a slight but significant reduction in fat-free mass after the intervention.

Weight and fat mass loss were greater during the first phase. Between baseline and mid-intervention adolescents lost on average 5.7 ± 4.3g body weight and 4.3 ± 1.9 % of fat mass *versus* 4.4 ± 3.3g and 2.1 ± 2.2 % during the second phase of the intervention ($p<0.0001$).

Table 1. Anthropometric and body composition changes throughout the 10-month weight loss multidisciplinary program.

	Baseline Mean (SD)	5 months Mean (SD)	10 months Mean (SD)	Time effect
Weight (kg)	94.3 (13.9)	88.9 (13.0)***	85.4 (14.4)***$$$	<0.001
BMI (kg/m²)	35.7 (4.5)	33.4 (4.7)***	30.9 (5.0)***$$$	<0.001
FM (%)	38.7 (3.3)	34.4 (4.1)***	32.0 (5.5)***$$$	<0.001
FFM (kg)	55.5 (7.1)	55.9 (6.9)	55.4 (6.8)** $$	0.003

T0: 0 month; T1: 5 months; T2: 10 months; BMI: Body Mass Index; FM: Fat Mass; FFM: Fat-Free Mass; SD: Standard Deviation; *: Significantly different from T0 (*p<0.05; **p<0.01; ***p<0.001); $: significantly different from T1 ($p<0.05; $$p<0.01; $$$p<0.001).

Energy intake, dietary profile and appetite sensations

As shown in Table 2, there was a significant time effect for lunch ad libitum energy intake ($p<0.001$) with a decrease of 198 kcal between T0 and T2 ($p=0.006$) and of 282 kcal between T1 and T2 (p<0.001). There was a non-significant increase in dinner (58 kcal) and decrease in total (139 kcal) ad libitum energy intake from T0 to T2.

The proportion of fat consumed decreased over time (p<0.001, with significant decreases between T0 and T2 and between T1 and T2 p<0.001), whereas energy intake derived from carbohydrate increased (p<0.001, with significant increases between T0 and T2 and between T1 and T2 p<0.001).

Regarding eating behaviors traits, uncontrolled and emotional eating decreased over time (p<0.001 between T0 and T2), whereas restrained eating remained stable.

Table 2. Energy intake, macronutrient consumption, appetite sensations and eating behavior trait changes throughout the 10-month weight loss multidisciplinary program.

		Baseline (T0) **Mean (SD)**	**5 months (T1)** **Mean (SD)**	**10 months (T2)** **Mean (SD)**	**Time effect**
Energy intake	Lunch EI (kcal)	1205.9 (284.1)	1290.5 (295.8)	1007.7 (250.6)$^{**\$\$\$}$	<0.001
	Dinner EI (kcal)	894.1 (254.9)	849.7 (187.5)	952.6 (200.5)	0.18
	Total EI (kcal)	2699.1 (435.8)	2740.1 (420.0)	2560.2 (367.3)	0.15
Macronutrients	Proteins (%)	22.7 (3.7)	23.1 (2.8)	21.9 (3.5)	0.19
	Fat (%)	32.2 (6.1)	31.4 (4.1)	21.8 (3.4)$^{***\$\$\$}$	<0.001
	CHO (%)	45.2 (8.0)	45.1 (4.5)	56.0 (3.7)$^{***\$\$\$}$	<0.001
Eating behaviors	Restrained eating	2.2 (0.4)	2.4 (0.5)	2.2 (0.5)	0.10
	Uncontrolled eating	2.6 (0.5)	2.4 (0.6)*	2.1 (0.5)$^{***\$\$}$	<0.001
	Emotional eating	2.4 (0.8)	2.3 (0.7)	1.9 (0.8)$^{***\$\$\$}$	<0.001

T0: 0 month; T1: 5 months; T2: 10 months; EI: energy intake; SD: Standard Deviation; *: Significantly different from T0 (*p<0.05; **p<0.01; ***p<0.001); $^{\$}$: significantly different from T1 ($^{\$}$p<0.05; $^{\$\$}$p<0.01; $^{\$\$\$}$p<0.001).

As shown in Figure 1, fasting hunger and fasting desire to eat both increased between T0 and T1 (p=0.02 and p=0.01, respectively) and decreased between T1 and T2 (p=0.02 and p<0.001, respectively). Fasting prospective food consumption decreased between T1 and T2 (p=0.048). There was a time effect for daily hunger and desire to eat (p=0.002 and p=0.02, respectively) with daily hunger increasing between T0 and T1 (p=0.001) and decreasing between T1 and T2 (p=0.008), and daily desire to eat decreasing between T1 and T2 (p=0.005). Daily prospective food consumption decreased between T1 and T2 (p=0.03).

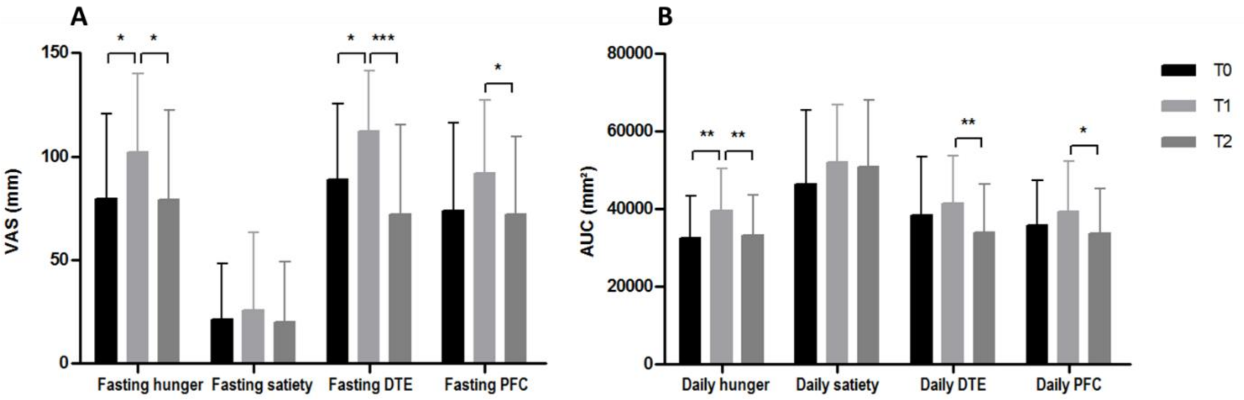

Figure 1. Fasting **(A)** and daily **(B)** appetite sensations throughout the 10-month multidisciplinary weight loss program. Solid bar: mean; Error bar: standard deviation; T0: 0 month; T1: 5 months; T2: 10 months; VAS: visual analogue scale; AUC: area under the curves; DTE: desire to eat; PFC: prospective food consumption; *: time effect (*p<0.05; **p<0.01; ***p<0.001).

Food reward

Regarding food reward (Table 3), main changes were found for explicit liking. We observed a time effect in the hungry state (pre-meal) for explicit liking for all food categories, which all increased between T0 and T1, then decreased between T1 and T2 (see Table 3 for details). In the fed state (post-meal), values in explicit liking for HFSA, LFSA and LFSW followed a different trend; they decreased from T0 to T1 then remained stable at T2. The interactions between time and meal revealed a different effect of the meal on explicit liking over time. Mainly, explicit liking decreased significantly from hungry to fed for each food category at T1 and T2 whereas at T0 there was no meal effect. In terms of implicit wanting, there were no meal, time or interaction effects at any time point.

Table 3. Food reward throughout the 10-month weight loss multidisciplinary program.

			Baseline (T0) Mean (SD)	5 months (T1) Mean (SD)	10 months (T2) Mean (SD)	Time effect	Meal effect	Interaction time x meal effect		
								T0 vs T1	T0 vs T2	T1 vs T2
Exp L	HFSA	Before	43.1 (27.6)	52.4 (23.9)*	38.1 (26.8)$^{\$\$}$	0.01	<0.001	<0.001	0.04	0.07
		After	39.7 (22.1)	21.5 (23.5)***###	19.9 (21.3)***##	<0.001				
	LFSA	Before	32.1 (22.1)	38.3 (19.1)*	24.3 (20.1)$^{\$\$\$}$	0.003	<0.001	0.001	0.20	0.06
		After	31.2 (20.1)	18.3 (20.6)***##	15.6 (21.7)** #	0.002				
	HFS	Before	48.2 (27.0)	59.0 (21.5)**	48.5 (26.9)$^{\$}$	0.01	<0.001	0.001	0.22	0.07
		After	39.7 (22.4)	28.9 (25.2)*###	31.2 (32.9)##	0.05				
	LFSW	Before	42.7 (23.3)	51.8 (23.8)**	35.9 (23.8)$^{\$\$\$}$	<0.001	<0.001	<0.001	0.02	0.07
		After	45.4 (25.2)	25.8 (25.2)***###	22.2 (25.6)***###	<0.001				
Imp W	HFSA	Before	3.0 (25.1)	-3.2 (26.9)	0.6 (19.1)	0.48	0.79	0.75	0.73	0.52
		After	2.0 (34.7)	-1.5 (26.9)	-2.7 (32.4)	0.77				
	LFSA	Before	-18.9 (25.5)	-20.3 (30.2)	-23.7 (22.8)	0.80	0.11	0.11	0.51	0.40
		After	-6.4 (42.4)	-21.4 (32.8)*	-16.9 (29.0) #	0.11				
	HFS	Before	14.1 (24.5)	17.7 (25.4)	19.2 (29.8)	0.84	0.72	0.07	0.09	0.97
		After	6.0 (30.3)	20.8 (36.3)*	24.4 (26.7)*	0.03				
	LFSW	Before	5.0 (20.9)	6.3 (25.2)	5.0 (20.3)	0.82	0.60	0.86	0.68	0.79
		After	5.4 (33.2)	4.6 (30.4)	0.9 (35.8)	0.83				

T0: 0 month; T1: 5 months; T2: 10 months; HFSA: high fat savory; LFSA: low fat savory; HFSW: high fat sweet; LFSW: low fat sweet; Exp L: explicit liking; Imp W: implicit wanting; SD: Standard Deviation; *: Significantly different from T0 (*p<0.05; **p<0.01; ***p<0.001); \$: Significantly different from T1 (\$p<0.05; \$\$p<0.01; \$\$\$p<0.001); #: Significantly different from pre-meal (#p<0.05; ##p<0.01; ###p<0.001).

Figure 2 illustrates the variability in food reward changes (hungry state) between the first phase (T0 to T1) and the second phase (T1 to T2) of the program. As highlighted, there was a clear trend for an increase in explicit liking during the first phase and a decrease in explicit liking during the second phase for all food categories. On the other hand, the variability in the change in implicit wanting was large and appeared to be evenly distributed across those that increased and those that decreased, resulting in little change in the overall mean.

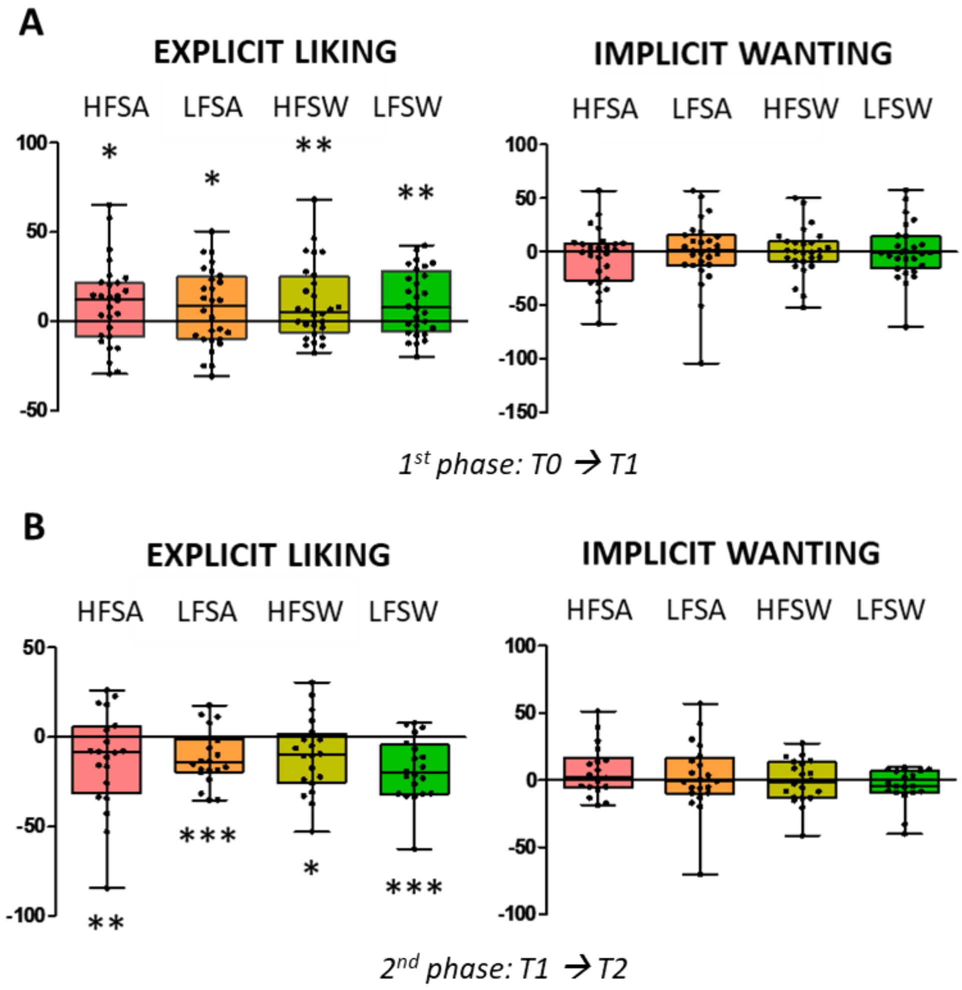

Figure 2. Variability among explicit liking and implicit wanting changes in the hungry state in response to a 10-month multidisciplinary weight loss program. A: Changes between T0 and T1; B: Changes between T1 and T2. T0: 0 month; T1: 5 months; T2: 10 months; HFSA: high fat savory; LFSA: low fat savory; HFSW: high fat sweet; LFSW: low fat sweet; *: significant differences between T0 and T1 or between T1 and T2 (*$p<0.05$; **$p<0.01$; ***$p<0.001$); the diagram shows the median, the lower and upper quartile and the individual variations.

Discussion

The present study suggests non-linear temporal changes in appetite and food reward during the 10-month multidisciplinary weight loss intervention in adolescents with obesity. Interestingly, our results suggest an increase in appetite and liking for all food categories mid-intervention, followed by a decrease at the end. Thus, the homeostatic and hedonic appetite adaptations to a multidisciplinary program might depend on the degree and timing of the weight loss, with opposite responses being observed between the first 5 months of intervention (phase 1) and the last 5 months (phase 2). Finally, after 5 months and until the end of the intervention, food consumption (ad libitum lunch meal) induced a decrease in explicit liking for all food categories, suggesting a reconnection between the hedonic and homeostatic systems of appetite control. Overall, this reduction in food reward was accompanied by a reduction in ad libitum energy intake at lunch and a slight reduction in daily energy intake.

In developed countries, the obesogenic environment – promoting a high-energy intake and a sedentary lifestyle – favors an hedonic rather than homeostatic control of food intake [1]. This shift toward an hedonic over an homeostatic control of eating behavior has been linked with reduced sensitivity to internal cues for satiety [33], leading to overeating. In the long term, the resulting positive energy balance is responsible for weight gain and then the development of overweight and obesity. In that context, obesity management has been subject to much research, aiming at improving both its prevention and treatment. Previous studies have shown that multifaceted approaches are more successful, leading to body composition, cardiovascular, metabolic and well-being improvements, compared with nutritional interventions alone [34]. Moreover, physical activity should be considered as an important component in weight management programs, especially since it is now recognized to affect not only energy expenditure, but also appetite control and energy intake [35]. While the first study examining the relationship between exercise and food intake in children was conducted 70 years ago [36], many others have been conducted since then demonstrating the beneficial effect of exercise on the control of food intake (for reviews see [15], [37]. While the homeostatic mechanisms linking exercise and food intake have been largely investigated lately, the neurocognitive pathways remain less explored, especially among youth. Identifying interventions that modulate the hedonic aspects of food intake in adolescents is of major interest given the current tendencies of the rates of obesity.

In that context, this study investigated for the first time the effect of a multidisciplinary weight loss intervention on food reward in adolescents with obesity. According to our results, distinct changes with the intervention occurred over the two phases. During the first 5 months of the intervention, we found an increase in explicit liking in the hungry state for all food categories. In a similar manner, subjective appetite sensations of hunger and desire to eat both increased during the first 5 months of the intervention. Although it did not reach significance, lunch energy intake and daily energy intake also slightly increased during this phase. Together these results suggest, in line with previous theories, the presence compensatory adaptations in appetite in the first phase of weight loss [38], [39]. The compensatory mechanisms observed during the first phase of the intervention in the current study are consistent with recently published results showing an increase in the subjective sensation of hunger [40] and energy intake [21], [22] after a multicomponent weight loss intervention in adolescents with obesity. A recent meta-analysis from Doucet et al. [39] synthetized the effect of weight loss on energy balance. According to them, there are both homeostatic and hedonic adaptations leading to an increase in appetite and drive to eat after weight loss. An attenuation of the anorexigenic peripheral signals (leptin, PYY, GLP-1) in response to weight loss may explain compensatory increases in food intake through weakened satiety [41]. On the other hand, weight loss via energy restriction has been previously associated with increases in food reward in adults with obesity [42]. However, if very few studies take mid-point measures, they may miss important temporal information occurring throughout an intervention. Indeed, we observed a different trend during the second phase of the program, leading to a decrease in explicit liking for all food categories, hunger, desire to eat, prospective food consumption and ad libitum lunch energy intake. These observations are in line with previous studies highlighting a reduced difficulty to maintain a stable body weight after weight reduction [43]. Klem et al. reported that the effort and the attention allocated to weight maintenance decreased as the duration of weight maintenance increased. In other words, the “cost” related to weight maintenance after weight loss appears to decrease over time. Importantly, during the second phase, weight and fat mass loss were lower, compared with the first phase of the intervention, suggesting that the degree of weight loss could be implicated in the compensatory mechanisms observed, with more rapid weight loss being counterproductive. It appears indeed that compensatory mechanisms are decreased in response to the slower weight loss period. These assumption need to be further investigated.

Moreover, while there were no changes in food reward in response to the meal at baseline, from the fifth month, the meal induced a significant decrease in food reward. As the reduction in food reward is typically observed from the hungry to fed states [44], [45], this lack of effect at baseline suggests that the reward system wasn't sensitive to homeostatic satiety signals at this time. This assumption is in line with a previous study from Stice at al. demonstrating that adolescents with obesity experienced less satisfaction from eating food compared with adolescents who are lean, due to a reduced response in the brain reward circuit [46]. Advanced theories support both a hyper-responsiveness of reward circuitry in the fasted state, and a hypo-responsiveness in the fed state in people with obesity, both increasing the risk for overeating [47]. Consequently, identifying interventions that can modulate these reward "abnormalities" is of high relevance to treat and prevent obesity. In a recent systematic review, Oustric at al. report a decrease in food reward after weight loss in adults with obesity (all interventions combined: dietary, pharmacological, behavioral and cognitive), and hypothesized that short term food deprivation may enhance food reward, whereas longer term deprivation might attenuate it (Oustric et al., 2018), which is in line with the present results.

The reduction of lunch ad libitum energy intake observed at 10-month is also in line with the systematic review by Schwartz et al. [10] who found that physical activity interventions in adolescents with obesity induced a decrease in daily energy intake. The reduction in daily energy intake in the current study was smaller in magnitude. Furthermore, we recorded an overall shift in macronutrient intake towards less fat and more carbohydrate, which couldn't be analyzed in the review from Schwartz et al. due to the lack of evidence regarding the relative contribution of each macronutrient (in percentage) to total energy intake. Further specific studies are therefore needed. One of the strength of the present study is the robust methodology we used to asses both energy intake (considering the relative contribution of fat, carbohydrate and protein) and food reward (considering liking and wanting). Indeed, as highlighted by Schwartz et al., the homeostatic appetite adaptations to weight loss are often considered as secondary outcomes and food intake is commonly assessed using dietary recall which is a highly subjective method, especially in this specific population. Instead of using a self-reported methods, we measured food intake via ad libitum buffet meals, which is most likely to reflect objective changes in food intake. Moreover, we used a psychometric methodology to assess food reward (the LFPQ), which provides a better reflection of the behavioral hedonic responses, compared with other methodologies using for example fMRI or BOLD signal. Finally, since it appears essential to better understand the control of energy intake throughout weight loss, we considered eating behavior traits of the participants as a variable of interest. Regarding these behavioural traits, we found coherent and encouraging results, demonstrating a significant decrease in emotional and uncontrolled eating, while restrained eating remained stable across time. As aforementioned, in the present environment favoring disinhibited eating and loss of control over eating, it is a priority to target the control of food intake and to reduce eating behaviors related with weight gain (e.g. emotional, external, uncontrolled and restrained eating) during weight loss interventions.

Interestingly, there were no overall changes in implicit wanting in response to the intervention and only mean liking was altered. A similar effect of changes in liking but not wanting in response to diet-induced weight loss was observed by Oustric et al. [48]. In their study, adult women were subjected to continuous or intermittent energy restriction to 5% weight loss within 12 weeks. In contrast, Beaulieu et al. report a reduction in wanting but not liking after a 12-week exercise training intervention in adults with overweight and obesity [49]. Together these results suggest potential differences in reward-related mechanisms affected by diet- and exercise-induced weight loss. This warrants further investigations, especially since some evidence suggests that wanting may be more important than liking in weight management [50]. Yet, there appeared to be more inter-individual variability in implicit wanting than in explicit liking. Almost as many adolescents had increases in implicit wanting as adolescents who had decreases, resulting in no overall mean differences. Exploratory analyses revealed no differences in outcomes between those that increased or decreased wanting (data not shown). Understanding what leads individuals to increase or decrease implicit wanting during weight loss, and the implications for weight management, is warranted.

The present results must be considered and interpreted in light of some limitations. First, the relatively small sample size did not allow us to further examine the inter-individual variability in the homeostatic adaptations to weight loss, which seems interesting in view of our results. Moreover, it would have been relevant to conduct a follow-up assessment to analyze whether the observed changes were maintained over time after the intervention. Finally, it would have been valuable to measure food reward using a French version of the LFPQ; however, at the time of our study, the French version had not yet been validated (the validation process is currently ongoing).

Conclusion

The present work is the first to evaluate the impact of weight loss on food reward in adolescents with obesity and provides new insights regarding the effect of a 10-month multidisciplinary intervention on both the control of food intake and appetite in this population. We show that mean liking in the hungry state increased during the first phase of the multicomponent weight loss program and returned to baseline after the completion of the intervention whereas liking in the fed state decreased during the first phase and remained unchanged in the second phase. No changes were observed for wanting.

Concurrently, appetite sensations and ad libitum energy intake increased during the first 5 months, followed by a reduction, suggesting that adaptive mechanisms to weight loss occurring in the short-to-medium term can be attenuated with persistence of weight loss in the longer term. The implications are that clinicians and patients need to be careful with potential compensatory adaptations occurring in the earlier phases of a weight loss intervention as this is a risky time for attrition and loss of motivation. Finally, while these results seem to reinforce the beneficial effect of a multicomponent weight loss intervention including exercise on the hedonic appetite system controlling food intake in adolescents with obesity, further work is required to understand the individual variability in the adaptations in appetite in response to weight loss.

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Discussion Générale

En France, depuis le *Programme National Nutrition Santé* lancé en 2001, comme au niveau international à travers la mise en place de la *Stratégie mondiale pour l'alimentation, l'exercice physique et la santé* développée en 2004 par l'Organisation Mondiale de la Santé ; les recherches visant à améliorer la prévention et le traitement de l'obésité pédiatrique se sont multipliées. La littérature actuelle suggère que pour être efficace la prise en charge se doit d'être multidisciplinaire et individualisée, reposant principalement sur un suivi et un soutien psychologique, une éducation nutritionnelle et diététique, ainsi qu'une programmation en activités physiques adaptées. Si l'efficacité de ces prises en charge multidisciplinaires a été bien démontrée sur les paramètres de la composition corporelle, du métabolisme et des fonctions cardio-vasculaires, leurs effets sur la régulation de la prise alimentaire sont moins documentés, en particulier chez l'enfant et l'adolescent.

Néanmoins, il est actuellement reconnu que la pratique régulière d'activité physique entraine des mécanismes d'adaptation, tant au niveau de la régulation des dépenses que des apports énergétiques. Ces mécanismes visent à maintenir l'homéostasie mais peuvent également composer de réelles limites à la réussite des programmes de perte de poids. Chez l'adulte (Hopkins et al., 2000), comme chez l'enfant (Sonneville & Gortmaker, 2008), l'augmentation du niveau d'activité physique a été associée à une augmentation de la prise alimentaire, rendant la perte de poids difficile voire impossible. Les travaux de Sonneville et Gortmaker ont mis en avant, dans une étude observationnelle prospective conduite auprès de 538 jeunes (âgés en moyenne de 11,7 ans), que pour chaque heure d'activité physique pratiquée en plus dans la journée, la prise alimentaire était augmentée de 292 kcal. D'après cette étude, l'activité physique ne permettrait pas d'induire un déficit énergétique sur le long terme. Il semblerait cependant qu'il existe une importante variabilité interindividuelle dans le degré de compensation, ce qui a amené certains auteurs à parler d'individus « répondeurs » *versus* individus « non-répondeurs » à l'activité physique. De plus, la modalité de pratique et son intensité semblent jouer un rôle déterminant dans ces adaptations nutritionnelles à l'exercice. Identifier et comprendre ces mécanismes d'adaptations permettrait, dans le cadre de la prise en charge de l'obésité, de modifier, si besoin, les réponses nutritionnelles à l'exercice, et *in fine*, d'améliorer les résultats escomptés.

L'augmentation de la prévalence de l'obésité est associée à des modifications des habitudes alimentaires et d'exercice physique liées à des changements environnementaux et sociétaux, qui favorisent un mode de vie « obésogène ». D'une part, l'urbanisme et les transports augmentent la sédentarité, et d'autre part, le marketing, les industries agro-alimentaires et la distribution favorisent la surconsommation d'aliments très caloriques. L'hyper-palatabilité et la disponibilité des aliments augmentent la sollicitation du système hédonique du contrôle de la prise alimentaire, au détriment du système homéostatique (Berthoud, 2012). Dans ce contexte, les sensations de faim et de satiété, ainsi que les réels besoins en énergie de l'organisme, ne semblent plus être les principaux déterminants de la prise alimentaire. Au contraire, des mécanismes cognitifs tendent à prendre le dessus sur le contrôle homéostatique des comportements alimentaires. Parmi ces voies de régulation, le circuit de la récompense alimentaire (« Food Reward ») est fortement sollicité. Ainsi, la motivation à obtenir une récompense alimentaire (« wanting ») et le plaisir éprouvé lors de cette récompense (« liking ») sont des déterminants principaux de la régulation des comportements alimentaires. Des études précédentes, réalisées chez l'adulte, indiquent que l'exercice entraine des modifications du système de la récompense alimentaire, qui pourraient potentiellement expliquer les réponses nutritionnelles observées post-exercice. Cependant, jusqu'à présent aucune étude n'avait questionné les modifications du Food Reward à l'exercice, aussi bien aigu que chronique, chez l'adolescent en situation d'obésité.

La réponse nutritionnelle à l'exercice semble également médiée par le rapport psychologique vis-à-vis de l'alimentation des individus (Emery et al., 2016). Parmi ces facteurs psychologiques, l'émotionalité, l'externalité, la restriction et la désinhibition ont été associés à la surconsommation alimentaire. Ces traits caractéristiques de la régulation des comportements alimentaires sont précurseurs de troubles hyperphagiques, dont il est important de tenir compte dans la prescription de l'activité physique. Chez l'adulte, l'étude de Sim et al. indique que les individus ayant un niveau de restriction cognitive important, augmentent leur prise alimentaire *ad libitum,* par anticipation de la pratique d'exercice physique (Sim et al., 2018). A l'inverse, les individus « non-restreints » ne modifient pas leur prise alimentaire *ad libitum,* indépendamment de la condition (exercice *versus* contrôle).

Compte tenu de ces précédentes études, l'exploration des mécanismes cognitifs impliqués dans la régulation des comportements alimentaires en réponse à l'exercice apparait nécessaire de manière à mieux comprendre les réponses nutritionnelles à l'exercice physique d'une part, et à identifier les individus potentiellement « répondeurs » ou « non-répondeurs » d'autre part. Nous nous sommes ici particulièrement intéressés à ces adaptations chez l'adolescent en situation d'obésité. Dans ce contexte, l'objectif principal de ce travail de thèse était d'investiguer les adaptations nutritionnelles à l'eactivité physique dans le cadre de prises en charge multidisciplinaires de perte de poids chez l'adolescent en situation d'obésité et de questionner les mécanismes cognitifs impliqués dans ces régulations.

Ainsi, l'objectif de notre première étude a été d'explorer les réponses nutritionnelles suite à 10 mois de prise en charge multidisciplinaire, incluant de l'activité physique régulière, chez l'adolescent en situation d'obésité. Cette étude a été publiée en 2019 dans le journal *Appetite*. L'originalité de ce travail se trouve en partie dans la méthode de mesure utilisée pour évaluer la prise alimentaire. Tandis que les précédentes études réalisées dans cette population avaient utilisé des enquêtes alimentaires (Carnier et al., 2013; King et al., 2007; Prado et al., 2015), nous avons mis en place des buffets *ad libitum* aux trois temps de mesure (au début de la prise en charge (T0), après 5 mois (T1) et à la fin de la prise en charge (T2)). Cette divergence dans les méthodes de mesure utilisées peut notamment expliquer nos résultats qui entrent en contradiction avec la littérature existante. En effet, nos résultats mettent en avant une augmentation significative de la prise alimentaire (de 256 kcal en moyenne) en fin de prise en charge, alors que, comme synthétisé dans une récente revue systématique et méta-analytique, les travaux précédemment publiés montrent une diminution de la PA en réponse à des prises en charge identiques chez des enfants en adolescents souffrant d'obésité (pour revue voir Schwartz et al. 2017). L'utilisation de recueils alimentaires représente effectivement un biais, en particulier dans cette population. Ainsi, il est très probable que les adolescents aient sous-estimé leurs apports énergétiques en fin de cure dans les précédentes études, ce qui limite la robustesse de leurs conclusions. Plus spécifiquement, nous avons questionné dans cette étude le rôle du profil psychologique des adolescents vis-à-vis de l'alimentation dans la réussite du programme de perte de poids et des réponses nutritionnelles observées. Nos résultats indiquent que l'augmentation de la PA est significativement supérieure chez les adolescents qui ont un haut niveau de restriction cognitive en fin de prise en charge (score ≥ 3 au DEBQ) ; par rapport à ceux qui ont un faible niveau de restriction cognitive (respectivement + 492 kcal *versus* + 112 kcal, p=0.015). De plus, 92% des adolescents « restreints » augmentent leur PA au terme du programme, contre seulement 53% parmi les « non-restreints ». Lorsque l'on s'intéresse aux modifications des traits psychologiques vis-à-vis de l'alimentation, les résultats indiquent une diminution significative de l'alimentation émotionnelle et de l'externalité, ce qui est encourageant à l'issue de la prise en charge. Le score de restriction cognitive moyen n'est, quant à lui, pas modifié au cours de la prise en charge. Toutefois, au niveau individuel, certains adolescents ont diminué leur niveau de restriction cognitive, tandis que d'autres l'ont augmenté. Nos analyses complémentaires montrent que les adolescents qui étaient initialement classés comme « non-restreints » et qui sont devenus « restreints » à la fin de la cure, augmentent leur PA de 558 kcal ; tandis que les adolescents initialement classés comme « restreints » et qui sont devenus « non-restreints » à la fin de la cure, n'augmentent leur PA que de 55 kcal. Par ailleurs, les résultats indiquent que les « bons répondeurs » (ceux qui perdent plus de 10% de leur poids initial) avaient un score de restriction cognitive significativement plus faible que les « mauvais répondeurs » avant la prise en charge (respectivement 2.5 points *versus* 3.1 points, p=0.014). Ces résultats sont en accord avec l'étude de Ho et al., dans laquelle les auteurs trouvaient une association entre la diminution de la restriction cognitive et la perte de poids au cours d'un programme de prise en charge de l'obésité chez l'adolescent (Ho et al., 2013). Ensemble, ces résultats s'opposent à la croyance populaire que la restriction cognitive serait favorable à la perte de poids. Au contraire, ce trait du comportement alimentaire ne semble pas être un facteur de réussite des interventions de gestion du poids. Comme le décrit Barzic, l'individu restreint « *cesse de sélectionner sa nourriture en fonction du plaisir qu'elle va lui procurer et détermine ses choix à partir de ce qu'il sait ou « croit savoir » des propriétés diététiques des divers aliments. Il adopte une disposition intérieure vis-à-vis de la nourriture par laquelle il substitue la raison au plaisir en se contraignant à privilégier les informations cognitives au détriment de ses propres sensations physiologiques pour choisir sa nourriture* » (Barzic, 2008). En outre, comme décrit dans la littérature, les individus restreints sont plus vulnérables aux stimuli alimentaires et sont susceptibles d'augmenter leur consommation alimentaire dans des situations tentantes. Les buffets *ad libitum* que nous avons réalisés reflètent donc certainement ce trait de désinhibition alimentaire chez les adolescents cognitivement restreints.

Face à la progression alarmante de l'obésité, praticiens et scientifiques sont à la recherche de nouvelles méthodes et modalités de prise en charge de manière à améliorer les programmes multidisciplinaires classiques. Dans le domaine de l'activité physique, l'entrainement intermittent de haute intensité, par exemple, a été développé et a montré son efficacité clinique chez l'adolescent en situation d'obésité (García-Hermoso et al., 2016; Thivel et al., 2019), comme chez l'adulte (Keating et al., 2017). Toutefois, malgré des résultats prometteurs concernant les paramètres de la composition corporelle, du métabolisme et de la santé cardio-vasculaire, aucune étude n'avait, à notre connaissance, questionné le rôle de l'entrainement par intervalles de haute intensité sur la régulation de la prise alimentaire auprès de ce public. Cela fut l'objet de notre seconde étude. Il a plus précisément été question ici de comparer l'effet de deux programmes multidisciplinaires de perte de poids de 4 mois combinant des modalités d'exercices différentes, sur les comportements alimentaires d'adolescents en situation d'obésité. Un groupe « MICT » s'est entrainé en continu à intensité modérée, à 60% de VO_2max, 60 minutes 2 fois par semaine, tandis que le groupe « HIIT » a lui suivi un programme d'exercice intermittent de haute intensité (débutant à 75% pour atteindre en fin de prise en charge 90% de VO_2max), 15 minutes 2 fois par semaine. Nos principaux résultats montrent, en accord avec notre première étude, une augmentation significative de la prise alimentaire au terme des deux interventions. Les 2 programmes de perte de poids induisent en effet une augmentation similaire de la prise alimentaire (+615 kcal dans le groupe MICT *versus* +643 kcal dans le groupe HIIT). Nos résultats indiquent également une réduction de la masse grasse significativement supérieure dans le groupe HIIT par rapport au groupe MICT. Ainsi, pour un temps de pratique 4 fois plus court (60 minutes *versus* 15 minutes), le HIIT entraine des adaptations similaires de la prise alimentaire et une perte de masse grasse plus importante. Cette étude renforce l'intérêt de cette modalité de pratique, par rapport au MICT, dans la prise en charge de l'obésité pédiatrique. Comme observé dans notre première étude, nos résultats soulignent qu'indépendamment de la modalité de prise en charge (MICT *versus* HIIT), les adolescents « restreints » (score ≥ 3 au DEBQ) réduisent significativement moins leur poids et leur IMC à l'issue de la prise en charge, par rapport aux adolescents « non-restreints » (-5 kg et -2 kg/m^2 chez les adolescents “restreints” *versus* -8 kg et - 3 kg/m^2 chez les “non-restreints”; $p<0.05$). De plus, la variation du poids (en kg) ainsi que la variation de la prise alimentaire *ad libitum* (en kcal) apparaissent significativement corrélées au score de restriction cognitive initial. Ainsi, les plus restreints sont ceux qui ont perdu le moins de poids et qui ont le plus augmenté leur prise alimentaire à l'issue de la prise en charge. Cette étude a donné lieu à une publication dans le journal *Applied Physiology Nutrition and Metabolism en 2019.*

Si les résultats de cette seconde étude suggèrent une réponse énergétique (prise alimentaire) identique quelle que soit la modalité de l'entrainement mise en place (ici

HIIT ou MICT), l'impact d'autres modalités de pratique doit être questionné. Notre équipe a par exemple récemment questionné ces adaptations nutritionnelles en réponse à des prises en charge basées sur des exercices concentriques *versus* excentriques (Étude TEXTOO). Dans l'étude TEXTOO, qui n'a pas été réalisée dans le cadre ce travail de thèse, 12 semaines de prise en charge multidisciplinaire incluant des exercices excentriques semblent permettre d'éviter l'augmentation de la prise alimentaire chez des adolescents souffrant d'obésité, contrairement à un programme similaire utilisant des exercices concentriques (Thivel et al., 2019, EJAP under review). L'étude TEXTOO a donné lieu à trois publications internationales auxquelles j'ai contribué.

Alors que nos deux études précédentes (Étude 1 et 2) ont questionné le rôle joué par le profil cognitif dans la réponse nutritionnelle à l'activité physique chez des adolescents en situation d'obésité ; notre troisième étude s'est intéressée, pour la première fois dans cette population, aux modifications du système de la récompense en réponse à l'exercice (travail publié dans *Physiology & Behavior* en 2018). Par ailleurs, alors que l'exercice aigu de haute intensité a été mis en avant pour ses effets bénéfiques sur la prise alimentaire subséquente (diminution) chez l'adolescent en situation d'obésité (Thivel et al., 2014), les réponses alimentaires à un exercice intermittent de haute intensité (HIIE) restent inexplorées en dépit de la popularité croissante de cette modalité de pratique. Nous avons donc ici questionné l'effet d'une session de 15 minutes de pratique à haute intensité par intervalles (de 70 à 90% de la fréquence cardiaque maximale) sur la prise alimentaire *ad libitum*, les sensations d'appétit et le Food Reward chez 33 adolescents en situation d'obésité. Seulement une étude avait questionné chez l'enfant l'effet de cette modalité de pratique sur la prise alimentaire, mais celle-ci était réalisée chez des sujets minces (Morris et al., 2018). De manière concordante aux résultats de la méta-analyse de Thivel et al., démontrant un effet « statut-pondéral dépendant » (Thivel et al., 2014), la prise alimentaire n'était pas affectée en réponse à l'exercice chez les sujets de cette étude (Morris et al., 2018). Chez l'adulte en situation d'obésité, l'étude d'Alkahtani et al. (Alkahtani et al., 2013) avait investigué l'effet d'une session à haute intensité par intervalles sur les sensations d'appétit et les préférences alimentaires. Cependant, la prise alimentaire effective n'avait pas été mesurée. Notre étude apporte donc des éléments de réponse novateurs venant compléter les données de la littérature. Nos résultats principaux indiquent que l'exercice intermittent à haute intensité induit un effet anorexigène chez l'adolescent en situation d'obésité. Nous retrouvons en effet une diminution significative de 7% la prise alimentaire *ad libitum* lors du repas suivant l'exercice par rapport à notre condition contrôle (p=0.014). Ces résultats semblent en accord avec les études précédentes puisqu'il avait été démontré qu'en aigu, l'exercice physique intense induisait une réduction de la prise alimentaire chez l'adolescent en situation d'obésité (Thivel et al., 2014). La question d'un continuum reliant les adaptations nutritionnelles à l'exercice chez l'individu mince d'un côté *versus* l'individu en situation d'obésité de l'autre, s'était posée préalablement dans la littérature, pointant particulièrement le rôle du tissu adipeux et de la masse maigre dans ces régulations alimentaires post-exercice. En ce sens, nous avons également questionné l'implication du degré d'obésité des adolescents dans la prise alimentaire post-exercice. De façon intéressante, l'effet anorexigène de l'exercice est d'autant plus élevé que le degré d'obésité est important (Miguet et al., 2018). Ainsi, les adolescents appartenant aux terciles les plus élevés d'IMC et de masse grasse, réduisaient davantage leur prise alimentaire lors de la condition exercice par rapport à la condition contrôle, comparativement aux adolescents appartenant aux terciles inférieurs d'IMC et de masse grasse. Enfin, tandis que quelques études apportaient des éléments de réponses quant à la modification du « Food-Reward » en réponse à un exercice aigu chez l'adulte, cette étude fût la première à investiguer cette question chez l'adolescent en situation d'obésité. Nos résultats montrent que la préférence relative pour les aliments sucrés et gras, ainsi que le wanting implicite pour les aliments gras étaient significativement diminués en réponse au repas *ad libitum* dans la condition exercice uniquement. De plus, alors que le wanting implicite pour les aliments sucrés était augmenté en réponse au repas dans la condition contrôle, ce dernier était diminué dans la condition exercice. Toutefois, ces résultats sont à interpréter avec précaution, d'autant qu'il semble y avoir des différences interindividuelles importantes dans les modifications du Food Reward post-exercice (Finlayson et al., 2009).

Finalement, dans une logique de prise en charge de l'obésité pédiatrique, la quatrième étude de ce travail doctoral s'est intéressée aux modifications du Food Reward à plus long terme, dans le cadre d'une prise en charge multidisciplinaire de 10 mois chez l'adolescent en situation d'obésité. Cette étude apporte des éléments de réflexion importants, notamment à propos du contrôle de la prise alimentaire au cours des différentes « phases » de la perte de poids. Le design de cette étude permettait en effet de distinguer 2 phases : de 0 à 5 mois, puis de 5 à 10 mois. Nos résultats semblent indiquer la mise en place de mécanismes compensatoires lors de la première phase du programme. Entre le début de la prise en charge (T0) et l'évaluation intermédiaire (T1), les sensations d'appétit étaient en effet augmentées, ainsi que la prise alimentaire *ad libitum* et le liking « avant-repas » pour toutes les catégories d'aliment. Cette phase de « résistance à la perte de poids » avait déjà été observée dans nos précédentes études (Miguet et al., 2018, Miguet et al. 2019) démontrant une augmentation de la prise alimentaire. Par ailleurs, la mesure du Food Reward indique que cette première phase s'accompagne d'une réduction significative du liking « après-repas » pour toutes les catégories d'aliments. Tandis qu'avant la prise en charge (T0) le repas n'induisait pas de modification du Food Reward, au bout de 5 mois (T1, mesure intermédiaire) ainsi qu'au terme des 10 mois de programme (T2), le liking était significativement réduit en réponse au repas ; suggérant que la perte de poids permet de (re)connecter le système hédonique au système homéostatique du contrôle de la prise alimentaire. Ces résultats sont encourageants dans le cadre de la gestion du surpoids et de l'obésité, puisqu'il semblerait que la prise en charge favorise une réponse hédonique adaptée et couplée aux signaux homéostatiques et à l'état énergétique de l'individu. En outre, durant la seconde phase du programme, la prise alimentaire *ad libitum*, la faim et le désir de manger étaient diminués, retournant aux valeurs initiales (T0). En accord avec nos précédentes études, l'alimentation émotionnelle était également significativement réduite à l'issue des 10 mois de prise en charge. Ainsi, si des mécanismes compensatoires se mettent en place durant la première phase du programme, en réponse à la perte de poids, ils semblent s'atténuer et être suivis d'une phase de stabilisation durant la seconde phase. Nos résultats confortent donc ceux des précédentes études, en faveur des prises en charge de longue durée, pour permettre cette phase de stabilisation (Julian et al., 2018; Khammassi et al., 2019). Il est toutefois important de souligner que l'analyse en groupe entier n'a pas permis de mettre en avant des modifications du wanting en réponse à la perte de poids, alors que certains travaux indiquent que le wanting a une part plus importante que le liking dans la gestion du poids (Finlayson & Dalton, 2012). Si une étude réalisée chez l'adulte avait rapporté des résultats similaires aux notres, en réponse à 12 semaines de restriction calorique (Oustric et al., 2019 UKCO abstract), Beaulieu et al. (Beaulieu et al., 2019 UKCO abstract), quant à eux, ont observé une réduction du wanting sans modification du liking sute à un programme de 12 semaines d'activité physique. Face à ces divergences importantes, il semble évident que les implications respectives du liking et du wanting dans la régulation du poids méritent d'être approfondies. De plus, la variabilité interindividuelle se doit d'être prise en considération et explorée. Nos résultats soulignent, en effet, une importante variabilité entre les individus dans la modification du wanting au cours de la prise en charge. Il semblerait que les variations du wanting soient corrélées aux variations de poids, de la composition corporelle et de la prise alimentaire (Miguet et al. en révision). Si ce travail est le premier à questionner les effets d'une perte de poids induite par prise en charge multidisciplinaire sur le Food Reward d'adolescents en situation d'obésité, nos résultats sont en accord avec ce qui a récemment été rapporté chez l'adulte dans une revue systématique (Oustric et al., 2018). Cette dernière établit que les interventions de perte de poids, incluant de l'activité physique régulière, induisent une diminution du liking et du wanting pour les aliments riches en énergie (Oustric et al., 2018).

CONTEXTE METHODOLOGIQUE DE LA THESE

Les résultats de cette thèse sont à interpréter au regard du contexte méthodologique des études. Ces dernières ont été menées en condition « écologique » dans des centres médicaux infantiles, auprès d'adolescents en situation d'obésité : la maison médicale Tza-Nou à la Bourboule et l'unité Sésame du Centre Médical Infantile à Romagnat. La réalisation de travaux de recherche dans un tel contexte génère donc des conditions expérimentales limitant parfois l'harmonisation des protocoles et la comparaison systématique des résultats obtenus.

Ainsi, conduire des travaux de recherche dans le cadre de prises en charge cliniques institutionnalisées limite la plupart du temps la flexibilité de recrutement. En effet, le nombre d'adolescents pouvant être inclus dans nos études dépendait directement du nombre d'adolescents intégrant les structures. Nos travaux auraient pu reposer sur l'inclusion d'échantillon de convenance mais nous avons tout de même fait le choix d'élaborer des calculs de puissance statistique. Nous avons donc parfois mobilisé les adolescents de plusieurs cohortes cliniques, ce qui peut expliquer la durée importante de la réalisation de certains protocoles. En effet, dans le cadre de notre étude II nous avons dû inclure les adolescents de 4 séjours différents du centre médical infantile de Romagnat pour atteindre un échantillon statistiquement satisfaisant. Ceci peut composer une limite puisque les séjours sont de 4 mois, réalisés en conséquence sur des saisons différentes, avec des organisations quotidiennes qui peuvent avoir été différentes (dépendante du nombre d'adolescents par cure, de leurs horaires d'école, etc) ; ceci ayant tout de même étant pris en compte dans les analyses.

Des plus, nos travaux ont été réalisés en collaboration avec deux centres médicaux, à la structuration des soins différente. En effet, le SSR Tza-Nou propose par exemple des séjours de 10 mois, alors que le CMI de Romagnat propose lui des séjours de 4 mois. Cela peut expliquer les durées différentes des études réalisées (étude I et IV : 10 mois ; étude

II : 4 mois). Néanmoins, nous avons tenté, autant que possible, la mise en place systématique des mêmes mesures expérimentales dans les deux structures pour harmoniser nos approches.

De manière importante, bien que nous ayons essayé d'harmoniser au mieux les mesures expérimentales entre les différents sites d'études et différents temps de mesures, la durée de réalisation de l'ensemble des travaux de cette thèse (4 années au total) a pu conduire à l'adaptation et à l'évolution des méthodes et outils employés, de manière à être en accord avec les évolutions des données disponibles dans la littérature. Ainsi, si les premiers travaux utilisaient par exemple la version originale du TFEQ pour évaluer le niveau de restriction cognitive alimentaire, nous avons fait le choix, sur les dernières études, d'utiliser la version pédiatrique développée et validée en 2017 (Bryan et al. 2018). L'évaluation du Food Reward est un autre exemple de ces évolutions méthodologiques. En effet, si au début de nos travaux aucune tâche cognitive n'était disponible pour évaluer le Food Reward en français, la collaboration de notre équipe avec l'équipe de recherche ACBE (Appetite Control and Energy Balance) de l'Université de Leeds nous a permis la traduction du Leeds Food Preference Questionnaire, qui a ainsi été intégré à nos travaux (études III et IV). Il est intéressant de noter que cette traduction française du LFPQ dans le cadre de mes travaux de thèse donne actuellement lieu à une étude de développement et validation de ce LFPQ en langue et culture française (étude LFPQ-fr en cours).

La limite majeure de ce travail pourrait résider dans l'absence de groupe contrôle dans nos 4 études (normo-pondérés et adolescents en situation d'obésité sans intervention), ou de groupe intervention sans activité physique (de manière à isoler les effets de l'activité physique). Si l'inclusion de tels groupes apparait importante sur le plan méthodologique, cela est actuellement inenvisageable sur le plan éthique. En effet, lors des démarches éthiques, il n'a pas été accepté d'inclure au sein d'une recherche clinique un groupe de patients (adolescents en situation d'obésité) ne bénéficiant pas sur plusieurs mois d'une intervention pouvant améliorer leur condition. De même, alors que l'activité physique a été décrite comme essentielle au sein des prises en charge cliniques, il n'est pas apparu possible de la retirer dans le cadre de ces séjours institutionnalisés. C'est pourquoi l'objectif de nos travaux a été d'étudier les adaptations nutritionnelles en réponse à des prises en charge multidisciplinaires incluant de l'activité physique chez l'adolescent en situation d'obésité.

Nos résultats doivent donc être interprétés au regard de limitations induites par le contexte de réalisation et l'évolution des outils.

Tableau de conclusion : Principales questions de recherche et principaux résultats.

	ÉTUDE I	ÉTUDE II	ÉTUDE III	ÉTUDE IV
OBJECTIFS	**Effet d'une prise en charge multidisciplinaire (10 mois) sur contrôle du comportement alimentaire, implication du profil cognitif.**	**Comparaison HIIT *vs* MICT sur contrôle du comportement alimentaire, implication du profil cognitif (4 mois).**	**Effet de HIIT en aigu sur contrôle du comportement alimentaire et circuit de la récompense.**	**Effet d'une prise en charge multidisciplinaire (10 mois) sur contrôle du comportement alimentaire et circuit de la récompense.**
COMPOSITION CORPORELLE	↓ Poids et IMC. ↓ Masse grasse, plus importante chez garçons. ↑ Masse maigre chez garçons, pas chez filles.	Meilleures améliorations de la composition corporelle en HIIT *vs.* MICT.	↓ Prise alimentaire *ad libitum* post-exercice plus importante chez adolescents avec dégré d'obésité élevé.	↓ Poids, IMC, masse grasse, masse maigre.
PRISE ALIMENTAIRE	↑ PA *ad libitum* + chez restreints. ↑ % protéines; ↓ % lipides et glucides.	↑ PA *ad libitum* indépendamment de la modalité d'entraînement.	↓ PA *ad libitum* post-exercice.	PA totale *ad libitum* reste inchangée. ↓ PA sur le repas du midi.
SENSATIONS D'APPETIT	Pas de modification des sensations d'appétit au cours de la prise en charge.	↑ Faim et désir de manger à jeun (indépendamment de la modalité d'entraînement).	Pas de modification des sensations d'appétit en réponse à l'exercice.	↑ Faim et DTE pendant la première phase de prise en charge (T0→T1). ↓ Faim et DTE pendant la deuxième phase (T1→T2).
CIRCUIT DE LA RECOMPENSE	∅	∅	↓ Post-repas de la préférence relative pour aliments gras et sucrés en condition EX. ↓ Post-repas de implicit wanting pour aliments gras en condition EX.	↑ Liking explicit pre-repas entre T0 et T1 puis ↓ Liking explicit pre-repas entre T1 et T2. ↓ Post-repas du liking explicit entre T0 et T1 puis stabilisation.
PROFIL COGNITIF	↓ Alimentation externe et alimentation émotionnelle. Restriction cognitive au début de la prise en charge corrélée négativement au % de poids perdu.	↓ Alimentation externe et alimentation émotionnelle. ↓ Poids et IMC plus faible chez adolescents restreints mais préservation de leur masse maigre.	∅	↓ Alimentation émotionnelle et désinhibition alimentaire.
CONCLUSIONS	**↑ PA *ad libitum* suite à prise en charge multidisciplinaire, effet plus marqué chez adolescents restreints. ↓ Poids plus faible chez adolescents restreints.**	**HIIT : plus efficace dans la prise en charge de l'obésité chez l'adolescent *vs.* MICT. Restriction cognitive : facteur limitant la perte de poids.**	**↓ PA *ad libitum* post-exercice chez adolescents avec degré d'obésité élevé. ↓ Préférene relative et implicit wanting pour aliments gras post-exercice.**	**↓ Liking explicit post-repas après 5 mois de prise en charge. Reconnection entre systèmes homéostatique et hédonique du contrôle du comportement alimentaire au cours de la prise en charge.**

↑ : augmentation ; ↓ : diminution ; ∅ : paramètre non mesuré ; PA : prise alimentaire ; EX : exercice ; IMC : indice de masse corporel ; HIIT : high intensity interval training ; MICT : moderate intensity continuous training ; DTE : désir de manger ; T0 : baseline ; T1 : 5 mois ; T2 : 10 mois

Conclusion

En conclusion, les travaux conduits dans le cadre de ce doctorat ont permis d'enrichir la littérature et les connaissances scientifiques concernant le contrôle de la prise alimentaire en réponse à l'exercice, aussi bien aigu que chronique, chez l'adolescent en situation d'obésité.

Nos résultats soulignent que les réponses nutritionnelles post-exercice sont dépendantes du profil psychologique vis-à-vis de l'alimentation des adolescents. En particulier, la restriction cognitive s'avère augmenter les mécanismes compensatoires mis en œuvre dans le cadre d'une prise en charge multidisciplinaire de perte de poids. En effet, les adolescents « restreints » augmentent davantage leur prise alimentaire *ad libitum* à l'issue des différentes prises en charge proposées (de durée variable, et comparant plusieurs modalités d'activité physique) comparativement aux adolescents « non-restreints ». Les adolescents « restreints » perdent également moins de poids. Il est donc primordial de veiller à ce que les politiques de santé publique ne mettent pas en place des stratégies de prises en charge restrictives, mais au contraire des interventions permettant la réappropriation de ses propres sensations physiologiques. En effet, les considérations nutritionnelles, telles que les interdits ou les régimes alimentaires, amènent l'individu à se référer à des signaux externes, et non plus internes, pour réguler sa prise alimentaire. Penser son alimentation en des termes rationnels pourrait donc détourner le consommateur de ses sensations et, *in fine,* diminuer ses capacités à identifier et à respecter sa faim ou sa satiété, et ainsi augmenter les quantités ingérées. L'exercice physique a une place importante dans le contrôle des comportements alimentaires. Nos résultats, ajoutés à ceux de la littérature, indiquent qu'il permet de réduire l'alimentation émotionnelle, l'externalité et la désinhibition alimentaire. De plus, aussi bien en aigu qu'en chronique, la pratique d'activité physique semble (re)connecter les systèmes hédonique et homéostatique du contrôle de la prise alimentaire. En effet, nos résultats indiquent qu'en réponse à l'exercice les composantes du système de la récompense sont significativement diminuées après le repas. La modification du système de la récompense post-exercice semble pouvoir expliquer, en partie, les réponses nutritionnelles observées chez ces adolescents.

PERSPECTIVES

Les études de ce travail doctoral, couplées aux données actuelles de la littérature, rapportent que la pratique d'activité physique favorise le contrôle de la prise alimentaire chez l'adolescent en situation d'obésité. Toutefois, dans les perspectives de recherche à venir, il apparait essentiel de questionner la persistance au long terme des réponses nutritionnelles observées dans les présentes études. En effet, il serait intéressant de suivre les adolescents, à l'issue de la prise en charge, pour évaluer l'évolution de leur prise alimentaire, de leur rapport à l'alimentation et du fonctionnement de leur système de la récompense. Les modifications du Food Reward observées à l'issue des 10 mois de prise en charge sont-elles durables dans le temps ? La diminution de l'alimentation émotionnelle et de l'externalité alimentaire persiste-elle ? Aujourd'hui ces questions restent sans réponse et nécessitent de futures investigations. En outre, questionner si le profil cognitif vis-à-vis de l'alimentation en fin de cure pourrait être un indicateur de la stabilisation du poids *versus* de la reprise de poids s'avère pertinent. Identifier les adolescents susceptibles de reprendre du poids en fin de cure permettrait d'intensifier leur suivi et de favoriser la stabilisation de leur poids.

Par ailleurs, si nous avons évalué l'impact du profil cognitif vis-à-vis de l'alimentation sur les réponses nutritionnelles à l'exercice, l'effet de la perception de l'activité physique elle-même reste moins explorée. Pourtant, plusieurs études ont démontré que la représentation cognitive de l'exercice réalisé avait un impact sur la prise alimentaire post-exercice. Chez l'adolescent, Fearnbach et al. rapportent que la difficulté perçue de l'exercice réalisé est corrélée à la prise alimentaire post-exercice (Fearnbach et al., 2017).

De manière similaire chez l'adulte, les résultats de McCaig et al. indiquent que plus les individus pensent avoir dépensé un nombre important de calories durant l'exercice, plus ils augmentent leur prise alimentaire post-exercice (McCaig et al., 2016). Fenzl et al. ont comparé l'effet d'un même exercice labélisé de deux manières différentes : « exercice bruleur de gras » *versus* « exercice d'endurance » sur la prise alimentaire (Fenzl et al., 2014). Les résultats de leur étude indiquent que la qualification « exercice bruleur de gras » entraîne une augmentation de la prise alimentaire post-exercice, par rapport à la qualification « exercice d'endurance » (Fenzl et al., 2014). Enfin, Schneider et al. rapportent que lorsque l'exercice est perçu comme une condition stressante, les participants augmentent leur PA par rapport à la condition contrôle, ce qui n'est pas le cas lorsque l'exercice n'engendre pas de détérioration émotionnelle (Schneider et al., 2009). Or, nombreux sont les adolescents en situation d'obésité qui perçoivent la pratique d'activité physique comme difficile, génératrice de mal-être ou même de souffrance. Dans ce cadre, investiguer le rapport vis-à-vis de l'activité physique chez l'adolescent en situation d'obésité et son évolution au cours d'une prise en charge multidisciplinaire de perte de poids, s'avère une piste intéressante à explorer pour comprendre les adaptations nutritionnelles post-exercice. Ainsi, les suites de notre travail de recherche pourraient s'intéresser à la valeur hédonique de l'activité physique chez l'adolescent en situation d'obésité. Dans cette perspective, nous envisageons le développement et la validation en français d'un questionnaire récemment mis en place aux États-Unis (Fearnbach et al., on going) évaluant la valeur hédonique et motivationnelle vis-à-vis de l'activité physique, tant dans sa dimension explicite, qu'implicite.

Pour finir, dans la perspective de développement de stratégies de gestion du poids plus efficaces, la réflexion devrait s'articuler autour de la dimension du plaisir et de la motivation des participants. En effet, il semble important de favoriser des prises en charge de l'obésité qui soient non restrictives et qui permettent la (re)connexion entre les systèmes homéostatique et hédonique du contrôle de la prise alimentaire. Les adolescents en situation d'obésité étant déjà pour la majorité d'entre eux dans un état de restriction cognitive, ont tendance à considérer les aliments comme des nutriments « bons » ou « mauvais » pour leur santé et à s'éloigner du rapport naturel qu'ils pourraient avoir vis-à-vis de l'alimentation. Pourtant, les mécanismes susceptibles d'entrainer l'adoption de comportements sains (quel que soit le domaine : activité physique ou nutrition) semblent plutôt provenir de la part affective et sensorielle des individus que de la part rationnelle de ces derniers. Maimaran et Fishbach ont montré que les stratégies instrumentalisant les aliments, dans le but d'orienter les comportements alimentaires vers des pratiques plus saines (du type « *la soupe fait grandir* » ou encore « *les carottes rendent intelligent* ») se révélaient souvent inefficaces voire contre-productives (Maimaran & Fishbach, 2014). Un mécanisme de rejet se met en place chez l'enfant, qui associe le fait que si un aliment est présenté pour ces vertus pour la santé, alors, c'est qu'il ne doit pas être bon au goût. Dans le domaine de l'activité physique, une étude s'est aussi intéressée à la relation entre plaisir et comportements sains (Perrin Petament, 1994). Dans son article, Claire Perrin étudie les liens entre les représentations vis-à-vis de l'activité physique, la manière de pratiquer et l'état de santé des individus. Les résultats de cette investigation ont permis de distinguer plusieurs profils selon le rapport aux activités physiques et sportives (APS) et à la santé : tandis que les hédonistes appréhendent les APS en termes de plaisir, les hygiénistes les considèrent comme un moyen d'atteindre une meilleure santé. Paradoxalement, les hédonistes pratiquent plus volontiers et se considèrent en meilleure santé que les hygiénistes, qui eux vivent leur état de santé de manière négative. Il apparait donc nécessaire de développer des stratégies de prise en charge centrées sur le plaisir et la motivation des participants.

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Annexes

PERTE DE POIDS : POURQUOI LA RESTRICTION N'EST PAS LA SOLUTION ?

Maud MIGUET, Alicia FILLON, Julie MASURIER, Yves BOIRIE, Martine DUCLOS, David THIVEL

Les profils alimentaires

Score de restriction	Score d'émotivité	Score d'externalité
Exercer un contrôle cognitif pour réduire sa prise alimentaire	**Manger en réponse à ses émotions**	Manger en réponse à des stimuli externes

Introduction

Les **régimes** et **la restriction alimentaire** sont des comportements fréquemment adoptés ; cela même chez des jeunes enfants ; particulièrement s'ils sont en situation de **surpoids** ou **d'obésité (Breat et al. 2008).**

***Cependant, ces stratégies sont controversées et leurs effets sur la perte du poids incertains* (Van Strien et al. 2014).**

Protocole

- ✓ 35 adolescents en situation d'obésité
- ✓ **10 mois** de prise en charge multidisciplinaire non restrictive
- ✓ A 0, 5 et 10 mois (T0, T1, T2) :
  - mesure du **profil alimentaire** *(questionnaire DEBQ + repas ad libitum)*
  - mesure de la **composition corporelle**

Résultats

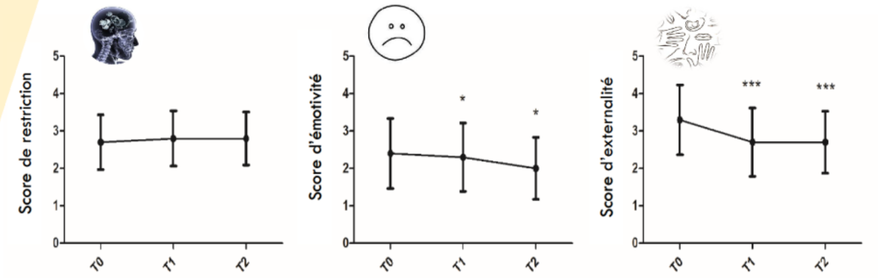


Fig.1 Variation des scores du DEBQ au cours de la prise en charge

❖ La prise en charge multidisciplinaire permet de diminuer le score d'externalité et d'émotivité sans modifier le niveau de restriction (Fig.1).

❖ Plus le score initial de restriction est faible, plus la perte de poids (en pourcentage) est grande (Fig2.).

❖ En fin de cure, lors d'une situation tentante de consommation (buffet *ad libitum*) les adolescents restreints ingèrent plus de calories que les non-restreints (Fig3).

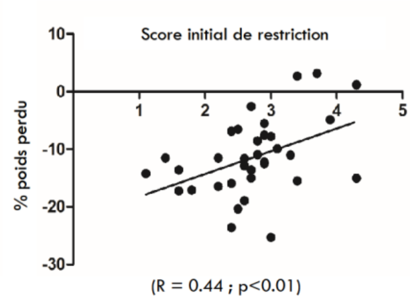


Fig2. Score de restriction initial et % de poids perdu

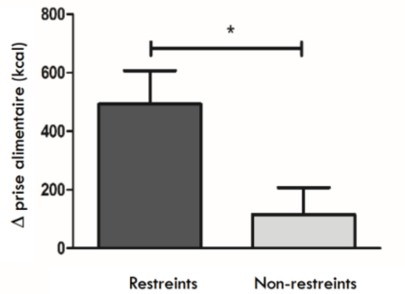
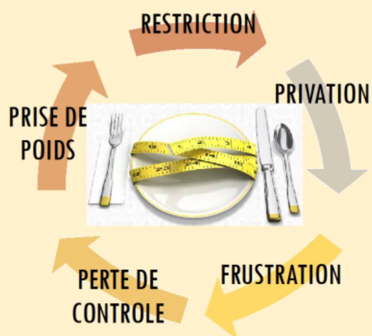


Fig3. Variation de la consommation alimentaire en fonction du profil de restriction

Conclusion

La perte de poids semble dépendante du profil alimentaire des adolescents. En effet, la restriction alimentaire n'apparait pas comme étant une stratégie efficace puisque les adolescents restreints perdent moins de poids et augmentent d'avantage leur prise alimentaire lors d'une situation tentante de consommation que les adolescents non-restreints.



Applications pratiques

✓

Prise en charge multidisciplinaire combinant :
- **Activité physique**
- **Éducation nutritionnelle** (travail sur les sensations de faim & de satiété; alimentation variée & équilibrée)

✗

Interdiction
Régime
Privation
Culpabilisation

- Braet, Claus, Goossens, Moens, Van Vlierberghe & Soetens (2008), *Journal of health psychology*
- Van Strien, Herman, Verheijden (2014), *Appetite*

Cognitive Restriction accentuates the increased energy intake response to a 10-month multidisciplinary weight loss program in adolescents with Obesity

Miguet Maud, Masurier Julie, Chaput Jean Philippe, Pereira Bruno, Lambert Céline, Dâmaso Ana Raimunda, Courteix Daniel, Duclos Martine, Boirie Yves, Thivel David

Introduction

What about the efficacity of multidisciplinary weight-loss interventions among adolescents with obesity ?

✓ Effective to improve body weight and body composition, physical fitness, cardio-metabolic profile, and health-related quality of life[1].

? Suffer from an important inter-individual variability[2], which could probably be explained in part by the individuals' cognitive status[3] and nutritional responses[4].

Aim

To explore the effect of a 10-month multidisciplinary intervention on body composition, energy intake and eating behaviors in adolescents with obesity, questioning whether cognitive restriction could be associated with the success of the intervention.

Methods

n: 35
12 boys and 23 girls

age: 13.4 (1.2)
BMI z-score: 2.2 (0.4)
BMI percentile: 98.0 (2.7)

10-month multidisciplinary weight loss program

2x/month — 4x60min/week — 1x/month

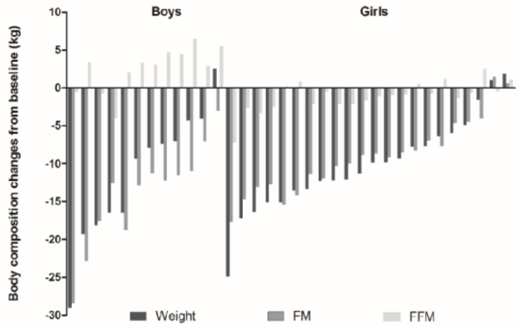
T0 — T1 — T2

3 days data collection (baseline, 5 months, end) :

- Body composition (Dual-energy X-ray absorptiometry)
- Resting metabolic rate: RMR (K4b²)
- 24hour Energy intake (*ad libitum* buffet meals)
- Appetite sensations (VAS)
- Cognitive restriction (DEBQ)

Results

Figure 1



Body weight, BMI & FM	**DECREASED** (figure 1)
RMR & Energy intake	**INCREASED** (figure A)
Cognitive restriction	**STABILIZED** (table 1)

Figure 2

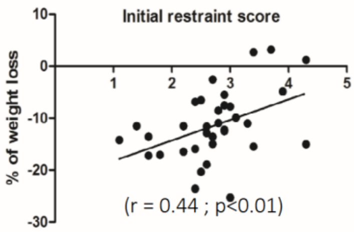


Table 1 Restraint score	T0 Mean (SD)	T1 Mean (SD)	T2 Mean (SD)
Boys	2.7 (0.8)	2.9 (0.9)	2.6 (0.7)
Girls	2.8 (0.8)	2.7 (0.6)	2.8 (0.7)

- No correlation between body weight, body composition, RMR and energy intake variations
- Initial restraint score negatively correlated with percentage of weight loss (figure 2)
- Cognitively restricted adolescents at the end of the intervention increased significantly more their *ad libitum* energy intake (figure B)
- 92% of the restrained eaters increased their *ad libitum* energy intake between T0 and T2 compared with only 53% in the non-restrained eaters (figure C)

Figure A

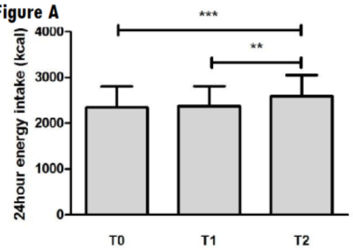


Figure B

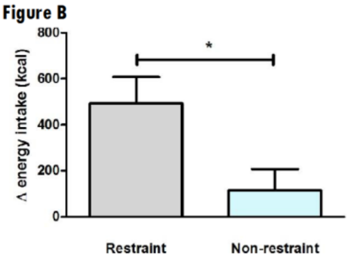
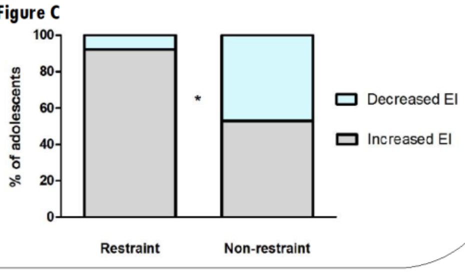


Figure C



Conclusion

A 10-month multidisciplinary weight loss intervention induced an increase in 24-hour *ad libitum* energy intake compared to baseline, especially in cognitively restrained eaters, which could potentially reflect their high disinhibition rate[5]. Moreover the adolescents who experienced the greatest weight loss at T2 were the less restrained at baseline.

Further longitudinal interventions are needed to determine the ability of specific eating behaviors in predicting good responders to a given weight loss intervention in adolescents with obesity.

References
[1] Knöpfli et al. 2008
[2] Jelalian et al. 2008
[3] Visona et al. 2002
[4] Schwartz et al. 2017
[5] Polivy and Herman, 1985

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Cognitive restriction accentuates the increased energy intake response to a 10-month multidisciplinary weight loss program in adolescents with obesity

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ABSTRACT

Background: Multidisciplinary interventions have shown some merits in weight reduction strategies in youth, however, their impact on subsequent daily energy intake remains largely unknown. The aim of the present study was to evaluate the nutritional responses to a 10-month multidisciplinary intervention among adolescents with obesity, in relation to their eating behavior characteristics.
Methods: Thirty-five adolescents (mean age: 13.4 ± 1.2 years) with obesity took part in a 10-month residential multidisciplinary weight loss program. Anthropometric measurements, body composition (dual-energy X-ray absorptiometry), 24-h *ad libitum* energy intake (weighted), eating behaviors (Dutch Eating Behavior Questionnaire) and appetite sensations (Visual Analogue Scales) were assessed on three occasions: at their arrival in the institution (T0), after 5 months (T1), and at the end of the 10-month program (T2).
Results: The mean weight loss reached 11% of the adolescents' initial body weight, with an important inter-individual variability (−25% to +3% of their initial body weight). Results revealed sex differences change, with boys showing a higher decrease in fat mass percent and increase in fat-free mass compared with girls. Weight loss was accompanied by a significant decrease in emotional (−8.3%, $p < 0.05$) and external (−14.8%, $p < 0.001$) eating scores and a significant increase in 24-h *ad libitum* energy intake (+246 kcal, $p < 0.001$). The observed subsequent increased 24-h *ad libitum* energy intake at T2 compared to T0 was significantly higher in cognitively restrained eaters (+492 kcal) compared to unrestrained eaters (+115 kcal, $p = 0,015$). Dietary restraint score at baseline was inversely correlated with the percentage of weight loss ($r = -0.44$, $p = 0.010$).
Conclusion: A 10-month multidisciplinary weight loss intervention induced an increase in 24-h *ad libitum* energy intake compared to baseline, especially in cognitively restrained eaters. Moreover, initially cognitively restrained eaters tended to lose less body weight compared to unrestrained ones. These findings suggest that cognitive restriction may be a useful eating behavior characteristic to consider as a screening tool for identifying adverse responders to weight loss interventions in youth.

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1. Introduction

Childhood obesity is a public health concern with one out of five children having obesity in Europe (WHO European Childhood Obesity Surveillance Initiative, 2016). Since obese adolescents have an 80% increased risk of becoming obese adults (Guo & Chumlea, 1999) and developing associated metabolic disorders that might increase their morbidity and reduce their life expectancy (Lifshitz, 2008), developing effective strategies to address childhood obesity remains a priority.

The social pressure to be thin has adverse effects by promoting body dissatisfaction, negative affects and disrupted eating attitudes and behaviors (Caqueo-Urízar et al., 2011), and concerns for dieting and cognitive restriction can start very early in children (Sinton & Birch, 2005; Tiggemann & Lowes, 2002). In particular, young overweight adolescents are reporting higher sociocultural and familial pressures to reach an ideal body weight. Although some cross-sectional studies highlight that restrained eating is positively associated with body weight (Braet et al., 2008; Megalakaki, Mouveaux, Hubin-Gayte, & Wypych, 2013; Vogels et al., 2006), it remains difficult to determine whether restrained eating is a cause or a consequence to overweight (Snoek, Strien, Janssens, & Engels, 2007; Wardle et al., 1992). Several studies have been conducted in adults, providing evidence for both increased (Chaput et al., 2009; Drapeau et al., 2003; van Strien, Herman, & Verheijden, 2014) or decreased body weight (Schaumberg, Anderson, Anderson, Reilly, & Gorrell, 2016) among dietary restrained individuals; however, this remains largely unexplored among children and adolescents. Studies are particularly needed regarding the potential effect of eating behavior traits, especially dietary restraint, on the success and efficacy of anti-obesity interventions among adolescents.

"Restrained eating" (i.e., cognitive effort to restrict energy density and food consumption (Hays & Roberts, 2008)) has been associated with potential risks for overeating through its association with disinhibition (i.e. the tendency to overeat in response to different stimuli (Polivy & Herman, 1985)). Cognitive restriction ignores appetite sensations and internal needs but refers to external rules and diet restrictions to regulate energy intake. Cognitive restriction could therefore appears as an ally to maintain (or lose) weight. Besides, when coupled with low disinhibition rate, cognitive restriction has been associated with beneficial dietary patterns and a successful weight management (Johnson, Pratt, & Wardle, 2005; Sarlio-Lähteenkorva & Rissanen, 1998). However, many studies highlighted the link between cognitive restriction and binge eating (Chaput et al., 2009; Drapeau et al., 2003; van Strien et al., 2014), which could explain why cognitive restriction is associated, on the long term, with weight gain.

Physical activity has recently been described as a good strategy for decreasing eating disorders, food reward and energy intake in adults and obese adolescents (Blanchet et al., 2018; Schwartz, King, Perreira, Blundell, & Thivel, 2017). Recently, Martin-Gracia et al. (Martín-García et al., 2017) found that a 3-month vigorous physical activity intervention decreased emotional eating in overweight boys and girls. In their systematic review, Schwartz et al. (Schwartz et al., 2017) concluded that physical activity interventions helped to decrease daily energy intake in adolescents with obesity. Such results suggest that the effect of physical activity interventions on overall health, body weight and body composition might be in part mediated by modifications in eating behaviors in youth with obesity. However, most studies relied on self-reported dietary intake, which, as indicated by previous work, is a major limitation for the interpretation of findings (Schwartz et al., 2017). Moreover, as obesity is a multifactorial disease, it appears essential to combine different disciplines to favor long-term improvements.

Multidisciplinary interventions combining physical activity, nutritional guidelines and psychological support are recommended among youth with obesity (Boff, RPA, Batista, de Souza, & Oliveira, 2017). Such interventions have been shown effective (at least in the short term), leading to significant improvements in body weight and body composition (Knöpfli et al., 2008), physical fitness (Knöpfli et al., 2008), cardio-metabolic profile (Bianchini et al., 2013), and health-related quality of life (Fonvig et al., 2017) among others. However, they have also been found to suffer from an important inter-individual variability in the response to the programs among adolescents (Jelalian et al., 2008). It thus seems important to better understand the main characteristics that can explain this variability in order to better individualize these programs. Eating behavior appears as one important candidate whose implication in the success of weight loss programs has to be explored (Harris & George, 2008; Visona & George, 2002).

Given the clinical importance of identifying the individual determinants that could help improving our long-term obesity reduction strategies, this study aimed to explore the effect of a 10-month multidisciplinary intervention on body composition, energy intake and eating behaviors in adolescents with obesity, questioning whether certain eating behavior traits of adolescents could be associated with the success of the intervention. This information is important because it could help to better screen for good and adverse responders to a weight loss program, and may provide additional tools to health care providers wishing to reduce the inter-individual variability generally observed for any given weight loss intervention.

2. Methods

2.1. Participants

A total of 35 adolescents (mean age: 13.4 ± 1.2 years) with obesity as defined by Cole et al. (Cole, Bellizzi, Flegal, & Dietz, 2000) (mean BMI z-score: 2.2 ± 0.4; BMI percentile: 98.0 ± 2.7) were enrolled in this study (12 boys and 23 girls) through local pediatric consultations. Convenience sampling was used in this study. To be included, the adolescents had to: i) be aged between 11 and 15 years; ii) present a BMI equal or above the 95th percentile for their gender and age (Cole et al., 2000); iii) be free of any medication that could interact with the protocol (e.g., thyroid medication, stimulant medication, medication for diabetes); iv) present no contraindication to physical activity; and v) take part in less than 2 h of physical activity per week (according to the International Physical Activity Questionnaire – IPAQ). All the adolescents and their legal representative received information sheets and signed up consent forms as requested by the ethical authorities.

2.2. Protocol design

After a medical inclusion realized by a pediatrician to ensure their ability to complete the study, the adolescents were enrolled in a 10-month residential multidisciplinary weight loss program in a local Pediatric Obesity Center (Tza Nou, La Bourboule, France). Maturation status was assessed by the physician using the Tanner stages during the first medical visit. Anthropometric measurements, body composition (dual-energy X-ray absorptiometry), resting metabolic rate (indirect calorimetry), daily energy intake (*ad libitum* buffet meals), eating behavior traits (Dutch Eating Behavior Questionnaire) and appetite sensations (visual analogue scales) were assessed before (T0), after 5 months (T1), and at the end of the 10-month program (T2). This study was conducted in accordance with the Helsinki declaration and received an ethical agreement from official authorities (CPP Sud Est VI: 2015-33; Clinical Trial NCT02626273).

2.3. Measurements

The following measurements have been performed on three different occasions (baseline, intermediaries and at the end of the 10-month intervention).

2.3.1. Anthropometric characteristics and body composition

Body weight and height were recorded to the nearest 0.1 kg and

0.5 cm, respectively, while wearing light clothes and bare-footed, using respectively a digital scale and a standard wall-mounted stadiometer. BMI was calculated as weight (kg) divided by height squared (m^2). Afterwards, BMI was reported in the sex and age dependent French reference curves to get the BMI percentile. Fat mass (FM) and fat-free mass (FFM) were assessed, under fasted state, by dual-energy X-ray absorptiometry (DXA) following standardized procedures (QDR4500A scanner, Hologic, Waltham, MA, USA).

2.3.2. Eating behavior traits

Eating behavior traits were assessed using the Dutch Eating Behavior Questionnaire (DEBQ) (Strien, Frijters, Bergers, & Defares, 1986). Three domains were evaluated: restrained eating (individuals' efforts to limit their food intake to control body weight or to promote weight loss; 10 items), emotional eating (excessive eating in response to negative moods; 13 items) and external eating (eating in response to food-related stimuli, regardless of the internal state of hunger or satiety; 10 items). Participants filled the 33 items in a six-point Likert scale (never (WHO European Childhood Obesity Surveillance Initiative, 2016), seldom (Guo & Chumlea, 1999), sometimes (Lifshitz, 2008), often (Caqueo-Urízar et al., 2011), very often (Tiggemann & Lowes, 2002) and not relevant (0)). Their answers were coded following the instructions given by Lluch et al. (Lluch et al., 1996). Means for each domain were calculated, with higher scores indicating greater endorsement of the eating behavior. Scores equal to or above three were used to categorize adolescents as restrained, emotional and/or external eaters (Antinori, 2004). This questionnaire has been previously validated in its French version (Lluch et al., 1996).

2.3.3. *Ad libitum* energy intake

Daily *ad libitum* energy intake was assessed during three single test days performed at baseline (T0), in the middle (T1) and at the end of the program (T2). At 08:00, after an overnight fast, the adolescents consumed a standardized calibrated breakfast respecting the recommendations for their age ($\approx$500 kcal) (Pradalie, 2003). Lunch and dinner meals were served *ad libitum* using a buffet-type meal. The content of the buffets was determined based on the adolescent's food preferences and eating habits. Top rated items as well as disliked ones and items liked but not usually consumed were excluded to avoid over-, under- and occasional consumption. At lunch, the menu was composed of beef steaks, pasta, mustard, cheese, yogurt, apple sauce, fruits and bread. Dinner menu was composed of ham/turkey, beans, mashed potatoes, cheese, yogurt, apple sauce, fruits and bread. Food items were presented in abundance and accompanied with tap water only. Adolescents made their choices and composed their trays individually before joining their habitual table (5 adolescents per table). Adolescents were told to eat until feeling comfortably satiated and had access to extra food if wanted. Food intake was weighted by the experimenters and the macro nutritive distribution (proportion of fat, carbohydrate and protein) as well as the total energy consumption in kcal were calculated using the software Bilnut 4.0. Total daily energy intake was calculated by summing up breakfast, lunch and dinner meals. This methodology has been previously validated and published (Thivel, Genin, Mathieu, Pereira, & Metz, 2016). Between the two *ad libitum* test meals, the adolescents were requested not to engage in any moderate to vigorous physical activity and mainly performed sedentary activities such as reading, homework, or board games.

2.3.4. Subjective appetite sensations

Appetite sensations were collected throughout the day using visual analogue scales (150 mm scales). Adolescents had to report their hunger, fullness, desire to eat and prospective food consumption at six regulated times: before and right after the breakfast, lunch, and dinner. The questions were i) "How hungry do you feel?", ii) "How full do you feel?", iii) "Would you like to eat something?", iv) "How much do you think you can eat?" (adolescents were asked to respond on a scale from "not at all" to "a lot"). This method has been previously validated (Flint, Raben, Blundell, & Astrup, 2000).

2.3.5. Resting metabolic rate

Resting metabolic rate (RMR) was measured in the morning, under fasted state, using indirect calorimetry (K4b^2, Cosmed, Rome, Italy). Before each test, gas analysis was calibrated in accordance with the manufacturer's recommendations. Participants extended in a supine position in a thermoneutral environment (22–25 °C room temperature) for 45 min before starting the measurements. After achieving a steady state, O_2 consumption and CO_2 production standardized for temperature, barometric pressure and humidity was recorded at 1 min intervals for 20–45 min and averaged over the whole measurement period. Resting metabolic rate (in kcal/day) and respiratory quotient (ratio of CO_2/O_2) were thereafter calculated.

2.4. Multidisciplinary weight loss program

The 10-month residential multidisciplinary weight loss program combined physical activity, nutritional education and psychological support. The physical activity intervention was composed of four 60-min physical activity sessions per week including aerobic training, strength training, aquatic activities and leisure-time activities (e.g. soccer). Concomitantly, the adolescents attended 2 h of physical education per week at school. The adolescents also attended nutritional education classes twice a month led by a dietician and received psychological support through individualized consultations with a professional once a month. During the intervention, the adolescents were submitted to a normo-caloric diet based on their age and sex recommendations (Murphy & Poos, 2002).

2.5. Statistical analysis

Statistical analyses were performed using Statview (version 4 for Windows) and Stata software, Version 13 (StataCorp, College Station, TX, US). All tests were two-sided, with a Type I error set at 0.05. Continuous data was expressed as mean $\pm$ standard deviation (SD) or median [interquartile range] according to statistical distribution. The assumption of normality was assessed by using the Kolmogorov-Smirnov test. Random-effects models for repeated data were performed to study the evolution between T0, T1 and T2 for weight, body composition, RMR, eating behaviors, *ad libitum* energy intake and macronutrient consumption among boys and girls. For appetite sensations, area under the curves (AUC) based on the trapezoid methods was also analyzed. Then, the following fixed effects were evaluate: *time*, *gender* and *time x gender* interaction, taking into account between and within patient variability (subject as random-effect). When appropriate, a Šidák's post-hoc test for multiple two by two comparisons was applied. The normality of residuals from these models was studied using the Shapiro-Wilk test. When appropriate, a logarithmic transformation was proposed to achieve the normality of dependent outcome.

Concerning non-repeated measures, quantitative variables were compared between groups by means of analysis of variance (ANOVA) or Kruskal-Wallis test when the assumptions of ANOVA were not met (normality and homoscedasticity analyzed using the Bartlett test). These analyses were conducted to compare (i) baseline parameters (e.g., weight, body composition) and their variation at the end of the 10-month intervention between restrained and non-restrained eaters, emotional and non-emotional eaters, and external and non-external eaters and (ii) eating behavior scores between adolescents who achieved more than 10% weight loss versus those who lost less than 10% of their initial body weight and (iii) energy intake between the four different trajectories of cognitive restraint during the 10-month weight loss intervention (i.e., restrained adolescents staying restrained; restrained adolescents becoming non-restrained; non-restrained adolescents staying non-restrained; and non-restrained adolescents becoming restrained). As proposed by some statisticians (Feise, 2002; Rothman, 1990) a particular focus will be given to the magnitude of differences, in addition to inferential statistical tests expressed using p-values. The results were expressed using Hedges's effect-sizes and regression coefficients with 95% confidence intervals. Categorical parameters were compared between groups using Chi-squared or Fisher's exact tests, notably to compare restrained and non-restrained responses to the *ad libitum* meal. The relationships between quantitative variables (more precisely between baseline eating behavior scores and weight and body composition variations) were studied estimating correlation coefficients (Pearson or Spearman, according to statistical distribution) applying a correction of type I error (Šidák's).

3. Results

3.1. Participant characteristics

Among the initial 41 children included, 35 completed the 10-month intervention (85% retention). Data analyses were performed on these 35 children. Of the six participants who left the trial, 1 dropped out for family reasons, 3 were excluded for disciplinary reasons, and 2 for school-related reasons. None of the drop outs was related to the study protocol.

Anthropometric and metabolic parameters were not significantly different among boys and girls at baseline. Changes are presented in Table 1. Body weight and BMI decreased significantly through the intervention in the same way for boys and girls. FM percent decreased significantly in both groups with a higher decrease in boys (p for interaction < 0.0001). FFM significantly decreased in girls during the intervention whereas it increased in boys (p for interaction < 0.0001). Inter-individual body weight, FM and FFM variations among boys and girls are presented in Fig. 1. Resting metabolic rate only changed among boys, with a significant increase. Resting respiratory quotient significantly decreased in both groups with no gender effect.

3.2. Energy intake, dietary profile and appetite feelings

As shown in Table 2, baseline dinner and whole day energy intake were higher in boys compared to girls. Boys ate more proteins (in grams and percentage). Both boys and girls showed increased *ad libitum* energy intake at the end of the intervention (boys increased energy intake at lunch, dinner and whole day; whereas girls increased their food consumption at dinner and whole day). Both increased the percentage of proteins and decreased the proportion of lipids and carbohydrates. At baseline, boys and girls showed similar restraint, external and emotional eating scores. Throughout the intervention, external eating scores decreased significantly in both groups; emotional eating scores decreased only in boys and restraint eating scores did not changed.

Fasting and daily hunger, satiety, desire to eat and prospective food consumption (assessed with visual analogue scales) were not significantly different between T0 and T2 (supplementary materials).

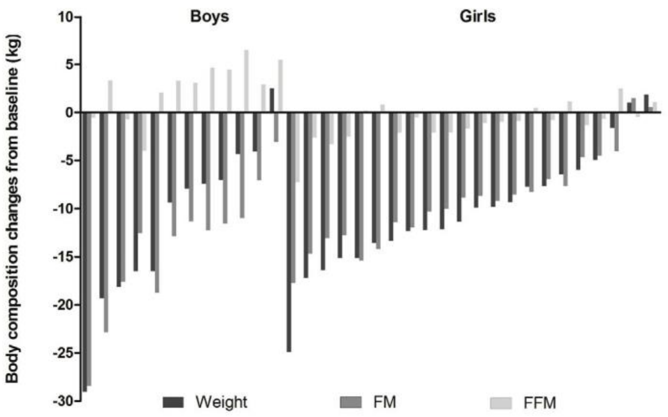

Fig. 1. Inter-individual differences in weight, fat mass (FM) and fat-free mass (FFM) variations in response to a 10-month multidisciplinary weight loss program among boys and girls.

3.3. Relationships between eating behaviors traits, energy intake and body composition

At baseline, significantly lower body weight and FFM were found in external eaters compared to non-external ones (82.6 *vs.* 97.0 kg for body weight, p < 0.01, hedges's g = 0.92 [0.22, 1.60], and 48.8 *vs.* 56.0 kg for fat-free mass, p < 0.05, hedges's g = 0.82 [0.13, 1.50]). FM

Table 1
Anthropometric and metabolic changes among boys and girls throughout the 10-month weight loss multidisciplinary program.

	T0 Mean (SD)	T1 Mean (SD)	T2 Mean (SD)	Time effect	Hedges g	Sex effect	Time x Sex	Regression coefficient
Weight (kg)								
Boys n = 12	90.8 (18.2)	83.5 (13.8)***	79.4 (12.5)$^{***\#}$	< 0.0001	**0.69 [0.20, 1.16]**	NS	NS	**1.25 [-2.30, 4.81]**
Girls n = 22	87.8 (16.7)	80.4 (14.8)***	77.6 (14.2)$^{***\#\#}$					
BMI (kg/m²)								
Boys n = 12	33.6 (4.6)	30.2 (3.8)***	27.9 (3.5)$^{***\#\#\#}$	< 0.0001	**1.14 [0.63, 1.64]**	NS	NS	**0.94 [-0.45, 2.33]**
Girls n = 22	33.5 (5.1)	29.8 (4.3)***	28.7 (4.1)$^{***\#}$					
FM (%)								
Boys n = 12	36.9 (5.8)	29.6 (5.0)***	25.4 (6.4)$^{***\#\#\#}$	< 0.0001	**1.41 [0.89, 1.93]**	0.0159	0.0001	**4.83 [2.81, 6.85]**
Girls n = 22	39.3 (4.7)	33.9 (4.9)^{a***}	32.6 (5.3)$^{b***\#}$					
FFM (kg)								
Boys n = 12	54.2 (10.6)	56.5 (9.2)**	56.8 (9.2)**	0.0244	**−0.03 [-0.50, 0.43]**	0.0906	< 0.0001	**−3.63 [-5.09, -2.17]**
Girls n = 22	50.8 (8.3)	50.7 (8.5)	49.7 (7.9)$^{a**\#}$					
RMR (kcal/day)								
Boys n = 11	2124 (377)	2597 (338)**	2596 (457)**	0.0003	**−0.56 [-1.07, -0.05]**	0.0042	NS	**−327.60 [-645.76, 9.43]**
Girls n = 15	1965 (354)	2150 (355)^{c}	2152 (387)^{c}					
RQ (VCO2/VO2)								
Boys n = 11	0.90 (0.10)	0.81 (0.04)**	0.80 (0.08)**	0.0001	**1.33 [0.77, 1.89]**	NS	NS	**0.01 [-0.06, 0.08]**
Girls n = 15	0.88 (0.04)	0.83 (0.06)	0.81 (0.09)*					

T0: 0 month; T1: 5 months; T2: 10 months; BMI: Body Mass Index; FM: Fat Mass; FFM: Fat-Free Mass; RMR: Resting Metabolic Rate; RQ: Respiratory Quotient; SD: Standard Deviation. a: significantly different between boys and girls with p < 0.05; b: significantly different between boys and girls with p < 0.01; c: significantly different between boys and girls with p < 0.001; *: significantly different with T0 with p < 0.05; **: significantly different with T0 with p < 0.01; ***: significantly different with T0 with p < 0.001; #: significantly different with T1 with p < 0.05; ##: significantly different with T1 with p < 0.01; ###: significantly different with T1 with p < 0.001.

Table 2
Energy intake and macronutrient consumption changes among boys and girls throughout the 10-month weight loss multidisciplinary program.

	T0 Mean (SD)	T1 Mean (SD)	T2 Mean (SD)	Time effect	Hegde g	Sex effect	Time x sex	Regression coefficient
Lunch EI (kcal)								
Boys n = 12	1031 (225)	1236 (281)[*]	1256 (222)[**]	0.0020	**−0.54 [-1.00, -0.07]**	0.0009	0.0770	**−141.95 [-305.01, 21.19]**
Girls n = 23	897 (238)	912 (240)[b]	980 (203)[c]					
Dinner EI (kcal)								
Boys n = 12	1036 (324)	940 (253)	1157 (309)[#]	0.0014	**−0.40 [-0.87, 0.07]**	0.0141	NS	**−10.73 [-189.60, 168.14]**
Girls n = 23	827 (236)[a]	802 (214)[t]	937 (241)[a*#]					
Total EI (kcal)								
Boys n = 12	2570 (502)	2679 (420)	2917 (484)[*]	0.0006	**−0.53 [-1.10, -0.52]**	0.0010	NS	**−152.68 [-421.82, 116.47]**
Girls n = 23	2228 (402)[a]	2218 (357)[b]	2422 (357)[b*#]					
Proteins (g)								
Boys n = 12	107.1 (30.6)	116.7 (29.9)	131.3 (23.7)[**#]	< 0.0001	**−1.25 [-1.76, -0.74]**	0.0009	NS	**12.41 [-4.17, 28.99]**
Girls n = 23	80.9 (20.3)[b]	84.8 (16.9)[c]	117.5 (23.2)[***###]					
Lipids (g)								
Boys n = 12	67.3 (23.3)	76.5 (22.8)	75.4 (27.3)	NS	**−0.11 [-0.57, 0.35]**	0.0056	NS	**−8.52 [-23.85, 6.81]**
Girls n = 23	56.7 (18.7)	55.8 (15.4)[b]	56.3 (20.3)[a]					
CHO (g)								
Boys n = 12	255.8 (54.7)	250.0 (45.2)	298.5 (54.4)[**##]	0.0020	**−0.36 [-0.82, 0.11]**	0.0083	NS	**−32.30 [-68.62, 4.01]**
Girls n = 23	223.0 (53.2)	215.1 (55.9)	233.5 (56.2)[b]					
Proteins (%)								
Boys n = 12	20.6 (2.6)	21.3 (2.7)	22.0 (3.2)	< 0.0001	**−1.42 [-1.94, -0.90]**	NS	0.0031	**4.51 [1.89, 7.13]**
Girls n = 23	18.8 (2.1)[a]	20.0 (2.2)	24.7 (3.6)[a***###]					
Lipids (%)								
Boys n = 12	29.1 (4.8)	31.3 (5.3)	27.5 (6.0)[#]	0.0211	**0.39 [-0.8, 0.86]**	NS	NS	**−1.26 [-5.93, 3.40]**
Girls n = 23	29.2 (5.4)	29.4 (5.4)	26.3 (7.6)[*#]					
CHO (%)								
Boys n = 12	50.0 (5.0)	46.4 (5.5)[*]	49.8 (4.0)[#]	0.0627	**0.40 [-0.07, 0.87]**	NS	NS	**−3.42 [-8.00, 1.12]**
Girls n = 23	52.1 (6.4)	50.0 (6.0)	48.5 (6.6)[*]					
Restraint score								
Boys n = 12	2.7 (0.8)	2.9 (0.9)	2.6 (0.7)	NS	**−0.02 [-0.49, 0.45]**	NS	NS	**0.06 [-0.48, 0.60]**
Girls n = 20	2.8 (0.8)	2.7 (0.6)	2.8 (0.7)					
External score								
Boys n = 12	3.3 (0.6)	2.9 (0.8)	2.7 (0.8)[*]	< 0.0001	**0.41 [-0.66, 0.89]**	NS	NS	**0.00 [-0.47, 0.48]**
Girls n = 20	3.3 (0.9)	2.6 (0.6)[***]	2.7 (0.6)[***]					
Emotional score								
Boys n = 12	2.8 (1.0)	2.5 (0.9)	2.2 (0.7)[*]	0.0187	**0.80 [0.30, 1.29]**	NS	NS	**0.32 [-0.27, 0.92]**
Girls n = 20	2.2 (0.9)	2.3 (1.0)	1.9 (0.9)					

T0: 0 month; T1: 5 months; T2: 10 months; SD: Standard Deviation; CHO: Carbohydrate; NS: Not Significant; a: significantly different between boys and girls with $p < 0.05$; b: significantly different between boys and girls with $p < 0.01$; c: significantly different between boys and girls with $p < 0.001$; *: significantly different with T0 with $p < 0.05$; **: significantly different with T0 with $p < 0.01$; ***: significantly different with T0 with $p < 0.001$; #: significantly different with T1 with $p < 0.05$; ##: significantly different with T1 with $p < 0.01$; ###: significantly different with T1 with $p < 0.001$.

did not differ between external and non-external eaters. Body weight, FFM and FM did not differ between restrained and non-restrained and between emotional and non-emotional eaters.

A significant inverse correlation was observed between the baseline cognitive restraint eating score and the percentage of weight loss ($p = 0.010$; $r = -0.44$), with the adolescents who experienced the greatest weight loss at T2 being the less restrained at baseline. No significant correlation was found between baseline restraint eating score and FM and FFM variations. Similarly, the baseline emotional score and baseline external score were not correlated with weight, FM and FFM variations.

The adolescents who lost more than 10% of their initial weight (at T2 compared with baseline) showed a restraint eating score at baseline that was significantly lower than those who lost less than 10% of their initial weight (2.5 *vs.* 3.1, $p = 0.014$, hedges's $g = 0.91$ [0.19, 1.63], Fig. 2A).

The FFM variation between baseline and T2 was significantly higher in restrained (≈ +2 kg) compared with non-restrained eaters (≈ −0.6 kg) ($p = 0.012$, hedges's $g = 0.98$ [0.21, 1.73], Fig. 2B). FM was not differently affected between restrained and non-restrained eaters. Emotional and external aspects of eating behavior did not influence differently fat mass or fat-free mass.

We did not find any significant correlation between body weight or body composition and energy intake variations. However, the adolescents who were cognitively restrained at T2 (end of the intervention) increased significantly more their *ad libitum* energy intake (+492 kcal in restrained eaters and +115 kcal in non-restrained eaters, $p < 0.05$, hedges's $g = 0.90$ [0.17, 1.62], Fig. 3A). Moreover, 92% of the restrained eaters increased their *ad libitum* energy intake between T0 and T2 compared with only 53% in the non-restrained eaters ($p < 0.05$, Fig. 3B).

Finally, we classified adolescents depending on their restraint profile modification: i) those who were restrained and became unrestrained (R » NR); ii) those who were unrestrained and stayed unrestrained (NR » NR); iii) those who were unrestrained and became restrained (NR » R); and iv) those who were restrained and stayed restrained (R » R). *Ad libitum* energy intake during the intervention did not change in the same way between groups (see Fig. 4). Time x profile interaction was < 0.05. We found a statistically significant difference between NR » NR and NR » R ($p < 0.05$; hedges's $g = -0.92$ [-1.81, −0.02]) and a tendency between R » NR and NR » R ($p = 0.07$; hedges's $g = 1.01$ [-0.08, 2.06]). In other words, adolescents who ate the most at the end of the intervention were those who were unrestrained and became restrained (+558 ± 484 kcal) while the adolescents who were restrained and became unrestrained ate less at T2 compared with baseline (+55 ± 445 kcal).

4. Discussion

The aim of this study was to evaluate the nutritional responses (i.e., energy intake, appetite sensations and eating behaviors) to a multidisciplinary weight loss program in adolescents with obesity and to

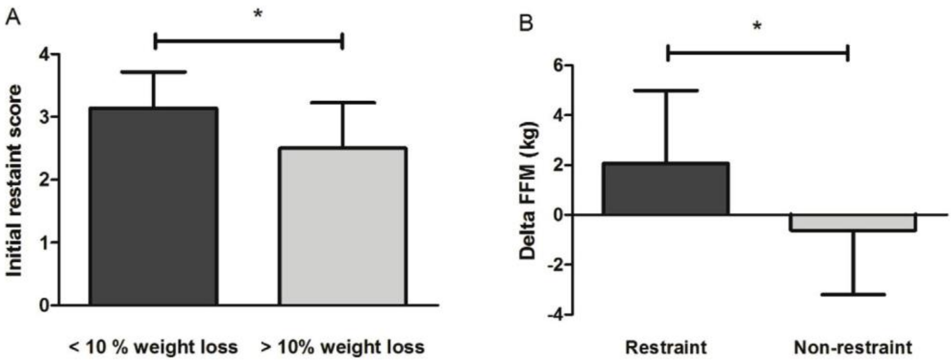

Fig. 2. A. Percentage of weight loss by initial restraint eating score. **B.** Fat-free mass variation depending on the dietary restraint subscale. **< 10% weight loss n = 12; > 10% weight loss n = 22; Restraint eaters n = 10; Non-restraint eaters n = 24; *p < 0.05.**

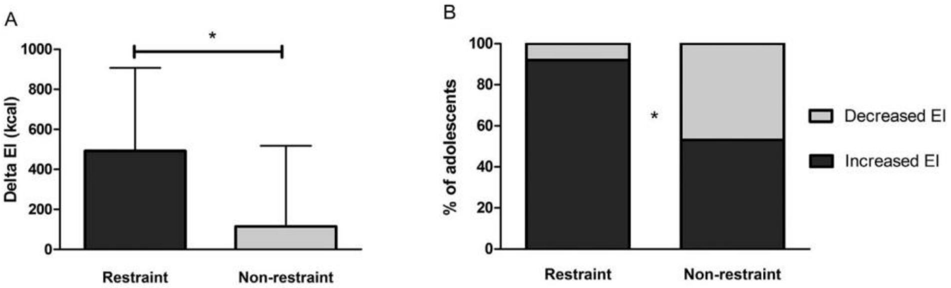

Fig. 3. A. *Ad libitum* energy intake variation between restrained and non-restrained eaters. **B.** Percentage of adolescents increasing or decreasing *ad libitum* energy intake among restrained and non-restrained eaters. **Delta EI: Energy Intake at T2-Energy Intake at T0; Restraint eaters n = 13; Non-restraint eaters n = 19; *: p < 0.05.**

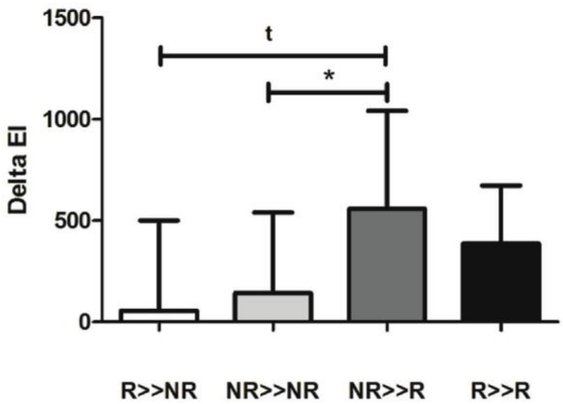

Fig. 4. *Ad libitum* energy intake variation depending on the trajectory of cognitive restraint between baseline and the end of the program. **Delta EI: Energy Intake at T2-Energy Intake at T0; R: Restraint; NR: Non-restraint; *: p < 0.05; t: p = 0.07.**

determine whether eating behaviors could be associated with the success of the intervention. We observed that weight loss was accompanied by a modification in the eating behaviors profile, with a significant decrease in emotional (−8.3%, $p < 0.05$) and external (−14.8%, $p < 0.001$) eating scores whereas 24-h *ad libitum* energy intake increased significantly (+246 kcal, $p < 0.001$). The observed subsequent increased 24-h *ad libitum* energy intake at T2 compared to T0 was significantly higher in cognitively restrained eaters (+492 kcal) compared to unrestrained eaters (+115 kcal, $p = 0.015$). Moreover, dietary restraint score at baseline was inversely correlated with the percentage of weight loss ($r = -0.44$, $p = 0.010$).

Contrary to the current body of evidence that suggests that multi-component interventions promote decreased daily energy intake in adolescents with obesity (Carnier et al., 2013; Prado et al., 2015; Thivel, Chaput, Adamo, & Goldfield, 2014), our results showed a significantly increased daily *ad libitum* energy intake (+246 kcal, $p < 0.001$) in response to a 10-month multidisciplinary program. This discrepancy could be explained by the different methodologies used to assess energy intake between the present work and the previous studies (for review see (Schwartz et al., 2017)). Indeed, as pointed out in a recent systematic review and meta-analysis, most studies have used self-reported dietary recalls, which remain highly subjective; whereas we used an objective measure of food ingestion (weighted *ad libitum* buffet meals). Self-reported dietary recalls have been shown to provide under-reported food intake, especially among obese adolescents (Burrows, Martin, & Collins, 2010), which could partly explain the observed differences between our results and the previous ones.

Although some previous works have shown an increased $PYY_{3\text{-}36}$ concentration concomitantly with a reduction of daily energy intake in response to a 4-month high-intensity training in obese youth (Prado et al., 2015), or increased anorexigenic factors concentration (AGRP and α-MSH) accompanied by decreased energy intake after a one-year multidisciplinary weight loss intervention in obese adolescents (Carnier et al., 2013) (both studies using self-reported methods to assess energy intake), other studies seem to obtain results that are in line with the increased energy intake observed in the present work. The increased energy ingestion observed in our study could be explained by the up-regulation of appetite hormones such as ghrelin as an adaptive response to energy deficit and weight loss (Foster-Schubert et al., 2005; Leidy et al., 2004). In their work, Gueugnon et al. (Gueugnon et al., 2012) found increased fasting ghrelin concentration accompanied by unchanged PYY (total form) after a 9-month multidisciplinary weight reduction program in adolescents with obesity. Their results are reinforced by the increased hunger profile and reduced satiety profile observed by King and colleagues after a 6-week weight loss intervention in a similar population (King, Hester, & Gately, 2007). According to the authors, lowering daily energy intake while increasing energy expenditure through exercise is effective in inducing weight loss but favors sensitive appetite regulation in children with obesity (King et al., 2007). Although the increased food consumption observed in the present work is in line with these previous results, we did not find any modification in daily appetite sensations (hunger, fullness, prospective food consumption and desire to eat) between baseline and the end of the study, which further supports the hypothesis that physical exercise might have an uncoupled effect on appetite feelings and energy intake in children and adolescents (Thivel & Chaput, 2014). Moreover, some studies have shown that ingestive behaviors are independent of appetite sensations in some context, where energy intake may be mainly driven by external and environmental factors, but not by hunger or fullness (Bilman, van Kleef, & van Trijp, 2017).

With regard to macronutrient consumption, our results showed an increase in the relative energy ingested from proteins between T0 and T2 (+4.4%, $p < 0.001$), while the energy derived from fat and CHO were found to be decreased (−2.5% and −2.4%, $p < 0.05$). Although the available literature indicates decreased intake of each macronutrients (fat, protein and carbohydrates) after chronic multi-component interventions in obese adolescents (Schwartz et al., 2017), these studies also used self-reported dietary evaluations that have been shown to provide unsatisfactory results in this population. The shift towards an increase in protein consumption could be related to the observed body composition variations, especially the preservation of fat-free mass.

Multidisciplinary interventions have been described and shown as good strategies for preventing and treating pediatric obesity and its health-related problems (Boff et al., 2017; Knöpfli et al., 2008; Bianchini et al., 2013; Fonvig et al., 2017). In support of these previous studies, weight, BMI and fat mass were decreased in response to our 10-month program combining physical activity, nutritional education and psychological support. Although the mean weight loss reached 11% of the adolescents baseline body weight, Fig. 1 illustrates an important inter-individual variability with 3 adolescents who did not lose weight and a body weight loss ranging from −25% to −2% of their initial body weight among those who did lose body weight. Interestingly, Fig. 1 also reveals sex differences. Indeed, boys were found to have different body composition adaptations than girls, with a higher decrease in fat mass percent and an increase in fat-free mass. This is in accordance with previous works (Knöpfli et al., 2008) (Christensen et al., 2018) which highlighted sex-specific changes after weight loss. A higher compliance and engagement in the physical activity program among boys compared with girls can be suggested to explain these differences, which is often observed in the general population (Telford, Telford, Olive, Cochrane, & Davey, 2016). As highlighted by Browning and Evans, the preservation of fat-free mass during weight loss appears to be an advantage because of the strong relationship between fat-free mass and resting energy expenditure (Browning & Evans, 2015). The authors specified that the maximization of resting energy expenditure is a desirable outcome in a perspective of long-term weight management. Our results precisely showed a significant increase in resting metabolic rate among boys, which is in line with their increased fat free mass. On the other hand, we found the respiratory quotient significantly decreased among both boys and girls in response to the intervention (indicating a shift in substrate utilization with higher fat and lower carbohydrate oxidation at rest). In line with another trial (Barwell, Malkova, Leggate, & Gill, 2009), this result is not surprising as it is well established that exercise (even without inducing negative energy balance) leads to increased fat oxidation (Hansen, Shriver, & Schoeller, 2005; Votruba, Atkinson, Hirvonen, & Schoeller, 2002), which favors weight stability (Seidell, Muller, Sorkin, & Andres, 1992).

With regard to eating behavior, previous works have shown that adolescents with obesity scored higher on restrained eating compared to normal-weight ones (Lluch, Herbeth, Méjean, & Siest, 2000; Wardle et al., 1992). In our study, we did not find initial weight or body composition differences between restrained and non-restrained eaters, which is not in line with the literature but could be explained by the high degree of obesity of our sample. Indeed, while most of the studies have been conducted so far among overweight and obese youth, our sample was composed of severely obese adolescents only. Similarly, at the beginning of the program, emotional and non-emotional eaters did not differ in weight, fat mass and fat-free mass. Yet, unexpected results were found concerning the external eating score. Indeed, contradictory to the theory of external eating, we found lower body weight in external eaters compared to non-external ones (respectively 82.6 *vs.* 97.0 kg body weight, $p < 0.01$). This result has already been found in previous studies (Lluch et al., 2000; Snoek et al., 2007; Wardle et al., 1992) with some authors suggesting a high influence of parents on overweight children, trying to regulate their food intake and food choices, reducing then their exposure to external food stimuli and making them less vulnerable to external stimuli.

As previously introduced, benefits of multidisciplinary interventions may be explained, among other mechanisms, by a modification of eating patterns and dietary profiles. Accordingly, our results indicate a decrease in emotional (among boys) and external (among boys and girls) eating scores (assessed by the DEBQ) after the 10-month residential multidisciplinary weight loss program. In other words, our intervention was effective in decreasing overeating in response to emotional and external situations, showing that adolescents better coped with emotional and external cues and referred more to internal cues. In line with our results, Martin-Garcia et al. (Martín-García et al., 2017) found decreased emotional eating scores after 3 months of vigorous physical activity in a similar population. Sarvestani et al. (Sabet Sarvestani, Jamalfard, Kargar, Kaveh, & Tabatabaee, 2009) also found decreased emotional and external eating scores in response to a 6-month multi-disciplinary intervention. Altogether, these results strengthen the importance of behavioral interventions on eating behavior in pediatric obesity strategies. Importantly, in contrast with Sarvestani et al. (Sabet Sarvestani et al., 2009), we did not find any increase in restraint score. This seems of particular interest in a weight loss perspective since restrained eating ignores appetite sensations and is therefore associated with binge eating. In that extent, Ho et al. previously demonstrated that a reduction in dietary restraint during a multi-component intervention among adolescents with obesity was associated with greater weight loss (Ho et al., 2013).

In a complementary analysis, we questioned whether the adolescents' initial eating behaviors could be associated with the success of the intervention. According to our results, there was a significant inverse correlation between adolescents' initial (baseline) cognitive restrained eating score and the percentage of weight loss. Similarly, the adolescents who lost less than 10% of their initial body weight were found to have a significantly higher cognitive restraint score compared to those whose weight loss exceeded 10% of their baseline weight. In contrast to popular beliefs, cognitive restriction does not seem to be a protective factor during weight management interventions. Several hypotheses may be considered to explain this observation. First, as suggested by the psychological theories on triggers overweight, cognitive restraint may be responsible for weight gain through overeating across binging (Polivy & Herman, 1985). Besides that, we found a significantly higher *ad libitum* food intake at the end of the program compared to baseline in restrained adolescents (versus non-restrained ones). As described in the literature, restrained eaters are more vulnerable to visual food cues (Hofmann, Ardelt-Gattinger, Paulmichl, Weghuber, & Blechert, 2015) and are susceptible to increase their food consumption in a tempting situation; especially if they envision a way to compensate this overconsumption (Urbszat, Herman, & Polivy, 2002). Indeed, Sim et al. (Sim, Lee, & Cheon, 2018) have recently demonstrated how exercise can be counterproductive among restrained eaters, when they considered physical activity as a compensatory health behavior, which "allowed" them to consume more calories. To that extent, cognitive restraint might be incriminated as a limited factor for weight loss achievement while it might, on the other hand, enhance the compliance to physical activity. In line with this hypothesis, we found a significantly higher fat-free mass variation between baseline and T2 in restrained (≈ +2 kg) compared with non-restrained eaters (≈ −0.6 kg, $p < 0.05$), which could, according to the compensatory health belief model (Knäuper, Rabiau, Cohen, & Patriciu, 2004), be explained by the previously observed higher engagement in physical activity among restrained versus non-restrained individuals (French, Jeffery, & Wing, 1994). In light of this previous work, it would have been valuable to have complementary data regarding their engagement in physical activity.

In contrast to most of the studies, which used self-reported disinhibition rate with questionnaires, an objective measure of eating disinhibition with *ad libitum* buffet meals was used in the present study. *Ad libitum* buffets are tempting situations that present an array of palatable foods and request self-control. Indeed, in the context of this experiment, children's ability to adjust their meal intake was solicited as well as self-discipline, as our design allowed children to overeat. Their consumption, therefore, reflects their disinhibition rate. The observed higher *ad libitum* energy intake (during our *ad libitum* test days) in restraint eaters is of particular importance and could explain the high rate of weight regain after weight loss interventions. Indeed, once the adolescents will leave the institution, they will be confronted to a high availability of food, which may challenge their eating self control and points out the necessity of nutritional education to prepare the post-intervention period. Further studies are needed to explore this post intervention period.

Aside from the behavioral adaptations that occur in restrained eaters, there is a combination of physiological characteristics that could explain the lower weight loss observed in restrained compared with non-restrained adolescents. Indeed, the previously underlined negative correlation between restrained score and leptin levels in both obese and lean individuals (Laessle, Wurmser, & Pirke, 2000; Prittwitz et al., 1997) may explain the lower resting metabolic rate found among restrained eaters in previous works (Laessle & Kikker, 2008), and thus their lowest weight loss against the non-restrained ones. Moreover, from a neurocognitive perspective, restrained eating has been linked with weight gain through modification in the spontaneous neural activity in food reward and inhibitory brain regions (Dong, Jackson, Wang, & Chen, 2015). In sum, even if the actual body of evidence seems to indicate a negative effect of cognitive restraint on weight management, further studies are needed.

Finally, the present study has to be interpreted in light of some limitations. Although we used *ad libitum* buffet meals as an objective measure of energy intake instead of self-reported diaries, our ecological setting might also compose a limitation. Indeed, the fact that the adolescents ate by small groups could have influenced their intake, which has not been assessed in the present work. The use of a convenience sample and the absence of a control group also have to be pointed out as potential limitations. Moreover, it would have been valuable to measure disinhibition using the Three Factor Eating Questionnaire; however, by the time of our study, the children version of the TFEQ (Bryant et al., 2018 Public Health Nutrition) was not validated yet, the French validation process being ongoing. We also could have added measurements of engagement in physical activity, perceptions about how demanding was the exercise or compensatory beliefs, as well as daily food intake (instead of just the three 24 h records at baseline, middle and end of the intervention), which has not been done for practical reasons. Finally, while this study seems to be the largest one conducted so far that investigates dietary profile and eating behaviors in adolescents with obesity after such a long multidisciplinary weight loss intervention, physiological and neurocognitive investigations are missing to provide some potential explanatory mechanisms. Nonetheless, we considered in our analysis the individual trajectory/history of cognitive restraint and their implications. Indeed, as showed by our last analysis, some of the adolescents turned from unrestrained at baseline to restrained by the end of the program while others switched from restrained to unrestrained, with *ad libitum* energy intake being significantly different between these two subgroups. Further studies are thus needed in this area.

In conclusion, the present results showed increased *ad libitum* energy intake in response to a multidisciplinary weight loss program among adolescents with obesity, without modification of their daily appetite feeling profiles. Importantly, we found that the adolescents' dietary restraint score was negatively associated with their weight loss achievement in response to the intervention, with initially high restrained eaters losing less weight. Restrained eaters were also found to increase significantly more (compared to unrestrained eaters) their *ad libitum* food intake at the end of the weight loss program compared to baseline, which could potentially reflect their high disinhibition rate. Further longitudinal interventions are needed to determine the ability of specific eating behaviors in predicting good responders to a given weight loss intervention in adolescents with obesity.

Conflicts of interest

The authors have no conflicts of interest to declare.

Declarations of interest

The authors have not conflict of interest to disclose.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.appet.2018.12.015.

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Appetite, energy intake and food reward responses to an acute High Intensity Interval Exercise in adolescents with obesity

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ABSTRACT

Background: High Intensity Interval Exercise (HIIE) is currently advocated for its beneficial effect on body composition and cardio-metabolic health in children and adolescents with obesity; however its impact on appetite control and food intake remains unknown. The aim of the present study was to examine the effect of a single HIIE session on subsequent energy intake, appetite feelings and food reward in adolescents with obesity.

Methods: Using a randomized cross-over design, *ad libitum* energy intake, subjective appetite, and food reward were examined in 33 adolescents with obesity (13.0 (± 0.9) years) following an acute high-intensity interval exercise (HIIE) *versus* a rest condition (CON). Absolute and relative energy intakes were measured from an *ad libitum* lunch meal 30 min after exercise or rest. Food reward was assessed using the Leeds Food Preference Questionnaire before and after the test meal. Appetite feelings were assessed using visual analogue scales at regular intervals throughout the day.

Results: *Ad libitum* food intake was significantly reduced after HIIE (lunch meal: −7 (± 23.7)%; $p = .014$ and whole day: −4 (± 14.7)%; $p = .044$), despite unchanged appetite feelings. HIIE was also found to decrease *ad libitum* meal food reward in adolescents with obesity: fat relative preference (from 3.3 (± 9.5) to 0.1 (± 8.0); $p = .03$), sweet taste relative preference (from −0.8 (± 13.9) to −5.0 (± 11.8); $p = .02$) and fat implicit wanting (from 22.3 (± 55.7) to −13.2 (± 58.5); $p = .01$) were significantly decreased in response to the *ad libitum* meal on HIIE. When considering the degree of obesity, it appears that the adolescents with higher BMI and higher fat mass percentage showed greater food intake reductions in response to HIIE (−21 (± 15)% for the third BMI tertile *versus* + 8 (± 30)% for the first BMI tertile $p = .004$; −15 (± 21)% for the third fat mass tertile *versus* + 8 (± 28)% for the first fat mass tertile $p = .017$).

Conclusion: A single HIIE session resulted in reduced subsequent energy intake and food reward in adolescents with obesity. Our results also seem to indicate that these nutritional responses depend on the adolescents' degree of obesity with a greater anorexigenic effect observed with higher obesity.

1. Introduction

There is an alarming progression of pediatric obesity with one out of four children concerned in European countries [1]. This obesity pandemic results in part from an energy imbalance between energy intake and expenditure, favored by the increasing availability of palatable

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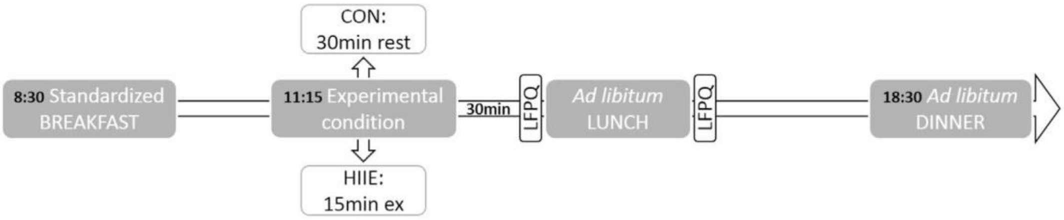

Fig. 1. Design of the experimental days. CON: rest condition; HIIE: high intensity interval exercise; LFPQ: Leeds Foos Preferences Questionnaire.

high-fat food, concomitantly with a clear decline in children's physical activity and progression of the time they spend sedentary [2]. Anti-obesity strategies that consider both sides of energy balance are therefore needed.

Evidence has shown that exercise energy expenditure and energy intake are loosely coupled variables, therefore we need a better understanding of their interactions [3]. Since the 1950s, many works have attempted to assess the role of daily activity-induced energy expenditure (from vigorous physical activity to sedentary behaviors) on energy intake in adults [4]. A recent systematic review in adults revealed there to be a better control of energy intake in active compared to inactive people, while individuals with very low levels of physical activity and high rates of sedentary behavior seem to suffer from a non-regulated control of food intake [5].

Although this relationship between exercise and energy intake has been mainly studied in adults for the last couple of decades, more attention has been recently paid to this question among children and adolescents, lean or obese [6-8]. According to the available evidence, while an acute bout of exercise does not seem to alter subsequent food consumption in lean children and adolescents [9, 10], an acute bout of intensive exercise (above 70% of the adolescent's maximal capacities) has been shown to significantly decrease food intake at the following meal in those with obesity [11]. This effect has been attributed to higher post-exercise anorexigenic gastrointestinal peptide concentrations [12] (such as peptide YY, glucagon-like peptide-1, and pancreatic polypeptide) and lower neurocognitive responses to food cues [13].

High-Intensity Interval Exercise (HIIE) has recently been described as an efficient exercise modality in adolescents with obesity, producing a lower perceived exertion and being at least as effective as moderate-continuous training to improve their body composition and metabolic profile [14]. Recent studies conducted in overweight adults also suggest that HIIE has similar effects on appetite sensations and hedonic liking and wanting for food than moderate intensity interval training [15]. Thus, HIIE does not appear to lead to a reward-induced increase in food intake [15]. The same team also found that a 4-week HIIE intervention was able to reduce hunger and the desire to eat, as well as to limit food compensation compared to a moderate-intensity program that tended to increase the preference for high fat food in overweight adults [16]. To our knowledge, there is so far no study that has examined the effect of HIIE on subsequent energy intake and appetite feelings in children and adolescents with obesity. Morris and collaborators recently examined the effect of a 22-min HIIE session composed of 30-s sprints on subsequent food intake in 10-year-old lean children [17]. According to their results, food intake and macronutrient preferences at the following meal were not affected, which is consistent with previous results from our teams showing that only overweight and obese youth modify their food consumption after an intensive bout of exercise [7].

The aim of the present study was to examine the effect of a single HIIE session on subsequent energy intake, macronutrient consumption, appetite sensations and food reward in adolescents with obesity. Secondly, we questioned whether these post-exercise nutritional adaptations could be influenced by the degree of obesity in adolescents.

2. Methods

2.1. Population

Thirty three adolescents with obesity (according to Cole et al. [18]) aged 12–15 years old (Tanner stage 3–4) participated in this study (12 boys and 21 girls). The adolescents were recruited through the local Pediatric Obesity Center (Tza Nou, La Bourboule, France). The adolescents and their parents were proposed to participate by the pediatrician during their regular medical visit in the center. To be included in the study, participants had to be free of any medication that could interact with the protocol (*e.g.* diabetic or blood pressure medications), should not present any contraindications to physical activity, and had to take part in < 2 h of physical activity per week (according to the International Physical Activity Questionnaire –IPAQ [19]). This study was conducted in accordance with the Helsinki declaration and all the adolescents and their legal representative received information sheets and signed up consent forms as requested by the local ethical authorities (Human Ethical Committee (CPP Sud Est VI) authorization reference: AU 1178 2015).

2.2. Design

After a preliminary medical inclusion visit made by a pediatrician to control for the ability of the adolescents to complete the study, they were asked to perform a maximal aerobic test and their body composition was assessed by Dual-energy X-ray Absorptiometry (DXA). The adolescents were then asked to complete a food preference questionnaire and the Three-Factor-Eating-Questionnaire R21 [20] in order to exclude children with high cognitive restraint. Afterward, adolescents were randomly assigned to one of two experimental sessions (see Fig. 1) performed one week apart: i) a rest condition without exercise (CON); ii) a High Intensity Interval Exercise condition (HIIE). On the two occasions, participants received a standardized breakfast (08:30) and started one of the two experimental conditions at 11:15 am (rest or exercise). Thirty minutes after the end of the experimental conditions (rest or exercise), participants had to complete the Leeds Food Preference Questionnaire (LFPQ) [21] before being served with an *ad libitum* buffet-style meal. They had to complete the LFPQ once more after the meal. Dinner energy intake was also assessed using an *ad libitum* buffet-style meal. Their appetite sensations were assessed at regular intervals through the day. Outside the experimental conditions and between the two *ad libitum* test meals, the adolescents were requested not to engage in any moderate to vigorous physical activity and mainly completed sedentary activities such as reading, homework or board games.

2.3. Anthropometric characteristics and body composition

Adolescents were weighed and had height measured wearing light clothing while bare-footed, using respectively a digital scale and a standard wall-mounted stadiometer. Body Mass Index (BMI) was calculated as weight (kg) divided by height squared (m^2). Afterwards, BMI was calculated in the sex and age dependent French reference curves to obtain the BMI percentile [22]. Fat mass (FM) and fat-free mass (FFM) were assessed by dual-energy X-ray absorptiometry (DXA) following standardized procedures (QDR4500A scanner, Hologic, Waltham, MA, USA). These measurements were obtained during the preliminary visit by a trained technician.

2.4. Maximal oxygen uptake test (VO2)

Each subject performed a V̇O2peak test on a traditional concentric ergometer [23]. The initial power was set at 30 W during 3 min, followed by a 15 W increment every minute until exhaustion. The adolescents were strongly encouraged by the experimenters throughout the test to perform their maximal effort. Maximal criteria were: heart rate > 90% of the theoretical maximum heart rate (210–0.65 × age), Respiratory Exchange Ratio (RER = V̇CO2/V̇O2) > 1.1 and/or V̇O2 plateau. Cardiac electrical activity (Ultima SeriesTM, Saint Paul, MN) and heart rate (Polar V800) were monitored and the test was coupled with a measurement of gas exchanges breath by breath (BreezeSuite Software, Saint Paul, MN), that determined V̇O2 and CO2 (Carbon Dioxide) production (V̇CO2). Volumes and gases were calibrated before each test. The V̇O2peak was defined as the average of the last 30 s of exercise before exhaustion.

2.5. Experimental conditions

2.5.1. Rest condition (CON)

Between 11:15 to 11:45 am, the participants remained seated on a comfortable chair (30 min). They were not allowed to talk, read, watch TV or to complete any intellectual tasks.

2.5.2. Exercise condition (HIIE)

Between 11:15 to 11:45 am, the participants were invited to perform a High Intensity Interval Exercise on an ergo-cycle, for a total duration of 15 min. Warming-up began at 60% of Maximal Heart Rate (HRmax) for 3 min. Then, adolescents had to perform 5 times the same pattern: 2 min intense bouts interspersed by active 30 s low intensity cycling. The intensity of the steps was as follows: 70%, 75%, 80%, 85%, and 90% HRmax. The intensity was controlled by heart rate records (Polar V800) using the results from the maximal aerobic capacity testing. Exercise induced energy expenditure was estimated afterwards based on the results obtained during the maximal oxygen uptake evaluation.

2.6. Perceived exertion

Immediately after exercise (HIIE session), the adolescents were asked to rate their perceived exertion using the Children's Effort Rating Table (CERT) from Williams et al. [24]. This scale was elaborated using a range of items from 1 to 10, the number 1 corresponding to an extremely easy exercise, while an effort leading the subject to interrupt the test because of its hard difficulty is indicated by 10.

2.7. Energy intake

At 08:00 am, the adolescents consumed a standardized calibrated breakfast (500 kcal) respecting the recommendations for their age (composition: bread, butter, marmalade, yogurt or semi-skimmed milk, fruit or fruit juice). Lunch and dinner meals were served *ad libitum* using a buffet-type meal. The content of the buffets was determined based on the adolescent's food preferences and eating habits. Top rated items as well as disliked ones and items liked but not usually consumed were excluded to avoid over-, under- and occasional consumption. Lunch menu was beef steak, pasta, mustard, cheese, yogurt, compote, fruits and bread. Dinner menu was ham/turkey, beans, mashed potato, cheese, yogurt, compote, fruits and bread. Adolescents were told to eat until feeling comfortably satiated. Food items were presented in abundance. Food intake was weighted by the experimenters and the macro nutritive distribution (proportion of fat, carbohydrate and protein) as well as the total energy consumption in kcal were calculated using the software Bilnut 4.0. This methodology has been previously validated and published [25].

2.8. Subjective appetite sensations

Appetite sensations were collected throughout the day using visual analogue scales (150 mm scales) [26]. Adolescents had to report their hunger, fullness, desire to eat and prospective food consumption at 12 time points (before and immediately after breakfast, 30 min and 60 min after breakfast, prior and after the experimental condition (CON or HIIE), before and immediately after lunch, 30 min and 60 min after lunch, before and right after dinner). The questions were i) “How hungry do you feel?”, ii) “How full do you feel?”, iii) “Would you like to eat something?”, iv) “How much do you think you can eat?”.

2.9. Food liking and wanting

The Leeds Food Preference Questionnaire (described in greater methodological detail by Dalton and Finlayson [27]) provided measures of food preference and food reward. Participants were presented with an array of pictures of individual food items common in the diet. Foods in the array were chosen by the local research team from a validated database to be either predominantly high (> 50% energy) or low (< 20% energy) in fat but similar in familiarity, protein content, palatability and suitable for the study population. The LFPQ has been deployed in a range of research [27] including a recent exercise/appetite trial in young French males [28]. Explicit liking and explicit wanting were measured by participants rating the extent to which they like each food (“How pleasant would it be to taste this food now?”) and want each food (“How much do you want to eat this food now? ”). The food images were presented individually, in a randomized order and participants make their ratings using a 100-mm VAS. Implicit wanting and relative food preference were assessed using a forced choice methodology in which the food images were paired so that every image from each of the four food types was compared to every other type over 96 trials (food pairs). Participants were instructed to respond as quickly and accurately as they could to indicate the food they want to eat the most at that time (“Which food do you most want to eat now?”). To measure implicit wanting, reaction times for all responses were covertly recorded and used to compute mean response times for each food type after adjusting for frequency of selection. Responses on the LFPQ were used to compute mean scores for high fat, low fat, sweet or savory food types (and different fat-taste combinations).

2.10. Statistical analysis

Sample size was determined according to previous works reported in literature [11] and to an estimation based on effect-size difference > 0.6, for a two-sided type I error at 5%, a statistical power at 90% and a correlation coefficient at 0.5 (two conditions for a same subject). For these assumptions, 32 subjects were enough to detect such true difference between the two conditions where our recruitment enrolled 33 subjects. Statistical analysis was performed using Stata software (version 13; StataCorp, College Station, Texas, USA) and Statview (version 4 for Windows). Continuous data were expressed as mean (± standard deviation (SD)). All tests were two-sided, with a Type I error set at 0.05. The normality of the data was checked using the Smirnov-Kolmogorov test. Adapted paired *t*-tests were used to compare absolute and relative energy intake, macronutrient preferences and energy expenditure between conditions (CON and HIIE). For appetite sensations, area under the curves (AUC, based on the trapezoid methods) were calculated and compared between CON and HIIE using t-test. To measure the *ad libitum* meal effect on relative preference, implicit wanting, explicit wanting and explicit liking, statistical analysis was conducted with linear mixed models to take into account the repeated measurements per subject. Interaction between time (before and after meal) and condition (CON and HIIE) was tested before performing subgroup analyzes. Our sub-analysis, questioning the effect of degree of obesity, children were classified in tertiles (based on weight, BMI, FM% and FFM kg as the main anthropometric and body composition indicators used in the literature to characterize obesity). One-way ANOVA were used to compare lunch energy intake, macronutrient preferences, and appetite sensations AUC on CON and HIIE between tertiles. Bonferroni post-hoc test were used when appropriate.).

3. Results

3.1. Characteristics of the participants

Thirty-three healthy adolescents with obesity were recruited for this study (11 boys, 21 girls). Participants had an average (± SD) age of 13.3 (± 0.9) years; weight: 93.2 (± 13.0) kg; BMI: 35.0 (± 4.3) kg/m^2; z-BMI: 2.3 (± 0.2); fat mass: 37.6 (± 3.5)%; fat free mass: 55.9 (± 7.3) kg and VO2peak: 23.5 (± 4.3) ml/min/kg.

3.2. Characteristics of HIIE and CON condition

Energy expenditure (EE) induced by exercise (total duration 15 min) was significantly higher compared to the 30-min resting energy expenditure (respectively 102 (± 21) kcal; and 52 (± 10) kcal; $p < .001$). The rate of perceived exertion by the end of the HIIE was 5.8 (± 2.0).

3.3. Energy intake

Absolute energy intake (EI) at lunch (HIIE: 1102 (± 276) kcal and CON: 1222 (± 310) kcal; $p = .014$; which represents a difference of 7%), as well as the total energy intake over the day (HIIE: 2062 (± 460) kcal and CON: 2177 (± 471) kcal; $p = .044$; which represents 4% difference) were significantly lower on HIIE compared with CON. Moreover, relative energy intake after lunchtime (REI = EI-EE) was also lower on HIIE compared with CON (1005 (± 274) kcal and 1172 (± 306) kcal respectively; $p = .001$) (Table 1).

3.4. Macronutrient consumption

The macronutrient intake expressed as both absolute intake (grams) and percentage of the total ingested energy, is shown in Table 2. On HIIE, the adolescents consumed significantly less protein and fat (in grams) at lunch compared to CON ($p = .008$ and $p = .022$). This difference is still significant regarding the total protein and fat content of the food consumed all day ($p = .020$ and $p = .033$). The carbohydrate consumption at lunch tended to decrease on HIIE compared with CON ($p = .058$).

Table 1
Energy expenditure, energy intake and relative energy intake, in response to high intensity interval exercise (HIIE condition) or rest (CON condition), in obese adolescents.

	CON	HIIE	p value
	Mean (± SD)	Mean (± SD)	
Lunch EI (kcal)	1222 (± 310)	1102 (± 276)	0.014
Lunch REI (kcal)	1172(± 306)	1005 (± 274)	0.001
Dinner EI (kcal)	955 (± 228)	960 (± 246)	0.877
Total EI (kcal)	2177 (± 471)	2062 (± 460)	0.044

CON: control condition; HIIE: high intensity interval exercise; EI: energy intake; REI: relative energy intake (EI-EE); SD: Standard Deviation; *: $p < .05$; **: $p < .01$; ***: $p < .001$, NS: not significant.

3.5. Subjective appetite sensations

Overall daily hunger, satiety, desire to eat and prospective food consumption were not different between conditions as illustrated by Fig. 2.

3.6. Food reward

Our results show a significant meal x condition interaction for taste implicit wanting ($p = .046$) with sweet taste implicit wanting increasing after the *ad libitum* meal on CON while decreasing on HIIE (see Table 3: a positive score for fat and/or taste biais indicates a preference for high fat and/or sweet food; a negative score for fat and/or taste biais indicates a preference for low fat and/or savory food). The before meal LFPQ results were not different after the rest or the HIIE condition. However, whereas no meal effect on CON was observed; fat relative preference, sweet taste relative preference and fat implicit wanting significantly decrease in response to the *ad libitum* meal on HIIE ($p = .026$, $p = .013$ and $p = .010$ respectively).

3.7. Effects of the degree of obesity

As detailed in the statistical analysis section, adolescents were classified in tertiles, depending on their degree obesity, according to four categories: weight, BMI, FM% and FFM (Table 4).

Regarding lunch energy intake depending of the degree of obesity, the delta between HIIE and CON was significantly different between the first and third BMI tertiles (ANOVA $p = .013$; post-hoc T1 *vs* T3 $p = .004$): a 21% lower energy intake (−287 (± 242) kcal) was observed after HIIE compared with CON in adolescents within the third BMI tertile, while those in the first one (then with a lower BMI) increased their food consumption at the lunch test meal by 8% (+33 (± 284) kcal) in response to HIIE. Similar results were observed when using FM% tertiles (ANOVA $p = .033$), where lunch food intake was lower in response to the HIIE session in the adolescents of the second and third FM% tertiles only (−15% (−219 (± 283) kcal) for the third FM% tertile and − 14% (−189 (± 222) kcal) for the second FM% tertile), while an 8% (+45 (± 225) kcal) increase was observed in the first FM% tertile (T1 *vs* T2: $p = .033$; T1 *vs.* T3: $p = .017$). The results are illustrated in Fig. 3.

The macronutrient consumption depending on the tertiles of obesity showed a significant BMI tertiles × conditions interaction on carbohydrate consumption (in grams) ($p = .015$): while the first BMI tertile (lower BMI) increased CHO consumption after HIIE compared to CON (+8 g), the second and the third BMI tertiles decreased their intake of CHO (−13.2 g and − 41.4 g). For the sensations of appetite, we did not find either any difference between tertiles.

4. Discussion

While HIIE is largely promoted as an efficient anti-obesity strategy thanks to its beneficial effects on body composition and cardio-metabolic health [14], less is known regarding its potential nutritional impacts. The present study examined for the first time the effect of a single HIIE session on subsequent energy intake, macronutrient consumption, appetite sensations and food reward in adolescents with obesity. According to our main result, an acute HIIE session reduced subsequent *ad libitum* food intake (at the following test meal and whole day), despite unchanged appetite feelings in 12–15 years old patients with obesity. HIIE was also found to decrease post *ad libitum* meal food reward in adolescents with obesity. Interestingly these nutritional responses seem to depend on the adolescents' degree of obesity.

Recently, Morris and collaborators explored for the first time the effects of HIIE on food consumption and appetite sensations in children [17]. Contrary to our results, their 22-minutes HIIE session composed of 30-second sprints did not affect subsequent food intake in lean children

Table 2
Absolute (grams) and relative (percentages) macronutrient consumption between meals during each experimental condition.

	CON		HIIE		*p* value	
	Grams Mean (± SD)	% Mean (± SD)	Grams Mean (± SD)	% Mean (± SD)	Grams	%
Lunch protein	64.3 (± 13.0)	21.4 (± 2.3)	58.6 (± 13.0)	21.5 (± 2.5)	0.008	0.801
Dinner protein	57.1 (± 15.8)	24.3 (± 6.2)	56.5 (± 14.5)	24.3 (± 6.2)	0.782	0.948
Total protein	121.4 (± 22.9)	22.6 (± 3.4)	115.1 (± 23.1)	22.7 (± 3.3)	0.020	0.994
Lunch fat	45.60 (± 9.6)	34.7 (± 8.6)	41.6 (± 9.8)	34.6 (± 6.0)	0.022	0.947
Dinner fat	33.5 (± 18.7)	30.2 (± 12.1)	32.0 (± 17.8)	28.3 (± 11.0)	0.430	0.120
Total fat	79.5 (± 22.5)	32.7 (± 6.1)	73.6 (± 22.7)	31.9 (± 5.9)	0.033	0.384
Lunch CHO	139.6 (± 54.8)	44.5 (± 8.0)	124.7 (± 47.5)	44.4 (± 8.9)	0.058	0.947
Dinner CHO	107.9 (± 29.4)	46.2 (± 11.7)	113.0 (± 29.9)	48.0 (± 9.9)	0.376	0.265
Total CHO	247.5 (± 70.7)	45.3 (± 7.1)	237.8 (± 66.7)	46.1 (± 7.03)	0.308	0.499

CON: control condition; HIIE: high intensity interval exercise; CHO: Carbohydrate; NS: not significant; SD: Standard Deviation.

[17]. Altogether, Morris et al. and our results confirm the actual literature clearly showing that intensive acute exercise can favor reduced energy intake in overweight and obese but not lean children and adolescents [7, 11, 29, 30]. These results add to the available evidence and suggest that HIIE might not only have beneficial effects on body composition, physical and cardio-metabolic fitness, but can also favor a transient negative energy balance, as illustrated by the significantly lower REI observed in the present work, as compared with a rest session. Importantly, this is accompanied by a low rate of perceived exertion, highlighting the acceptability and feasibility of such exercise modality in youth with obesity. While further chronic studies are needed to test the nutritional responses to long term High Intensity Interval Training, the observed transient anorexigenic effect of HIIE can be explained by some physiological and neurocognitive responses. Indeed, as already expressed in the literature, HIIE affects the concentrations of some of the main appetite-related peptides in adolescents with obesity, favoring increased PYY_{3-36} [31] and decreased active ghrelin [29]. Recent data suggest that post-intensive exercise energy intake modifications can also be explained by the response to exercise of some neural networks involved in the cognitive processing of food-related cues. In their work, Fearnbach et al. recently questioned the potential role played by such cognitive processing of food-related cues in the nutritional response to exercise in children and adolescents [13, 32]. Their results showed that the neural response reflecting the cognitive effort engaged in response to food stimuli is significantly reduced compared to non-food ones after a 45-minute cycling exercise set at moderate-to-high intensity in obese, but not lean adolescent boys [13, 32]. Importantly, this reduced neural activation was accompanied by a significant decreased energy intake at the following meal compared to a rest condition [32].

While all the previously published studies in the field have considered weight status, the present analysis also questioned whether the degree of obesity may influence the adolescents' post-exercise energy intake. According to this sub-analysis, the transient anorexigenic effect of exercise seems to be stronger in adolescents with higher BMI and higher fat mass percentage. Indeed, a 21% decreased energy intake was observed after HIIE compared with CON in adolescents within the third BMI tertile, while those in the first one (with a lower BMI) increased their food consumption at the test meal by 8% in response to HIIE. Similar results were observed when using FM% tertiles, where food intake was reduced in response to the HIIE session in the adolescents of the second and third tertiles only (−15% for the third tertile and −14% for the second one), while a 8% increase was observed in the first tertile. These results are consistent with previous works done by Fearnbach et al. who found body composition specific post-exercise neural responses to food cues [13, 33]. According to their results, body weight, BMI and FM are inversely correlated with the neural response to food stimuli following exercising [13]. In other words, they found that a higher index of adiposity was associated with lower brain responsiveness to food stimuli following 45 min-cycling exercise (at 65% VO2max). Thus, our results indicating a body composition specific nutritional post-exercise response may be explained by different cognitive processing of food stimuli: the greater post-exercise reduced energy intake in adolescents with the highest degree of obesity could be explained by a reduced neural response to food cues. Our results however failed to show any significant difference between FFM tertiles, which seems contradictory with the actual literature pointing a strong association between lean mass and daily energy intake in both adults and adolescents [34, 35] with Fearnbach et al. moreover showing a positive association between fat-free mass index and post-exercise intake in children at risk for obesity [36].

Interestingly, the reduced food consumption observed in the present work is not due to a particular effect on one specific macronutrient. Indeed, absolute protein, fat and CHO intakes at the test meal were all reduced (tendency for CHO) with no change of their respective contribution to the total energy ingested. Although the literature remains quite divergent regarding the macronutrient response to acute exercise, these results are in line with a recent systematic review suggesting that children and adolescents with obesity do not alter their relative macronutrient composition in response to acute exercise and calling for further specific researches [7]. Our secondary analysis however showed a significant BMI tertiles x CHO consumption interaction, with a higher CHO intake by the adolescents with lower BMI after HIIE while the adolescents of the second and the third BMI tertiles decreased their CHO consumption. More studies are needed regarding the potential effect of body composition on post-exercise macronutrient consumption.

Importantly, the observed post-exercise reduction in energy intake was not accompanied by any change in subjective appetite sensations (feelings of hunger, satiety, prospective food consumption or desire to eat); suggesting that this effect occurs without any food frustration in adolescents. This result is in line with previous works that have already highlighted this uncoupling effect of exercise on energy intake and appetite sensations in children and adolescents [37].

Elsewhere, evidence indicates that exercise may be link to food intake through its potential effect on food reward. If previous works have demonstrated the effect of exercise on explicit and implicit hedonic process in adults [15, 16, 38, 39], the present work is the first to question the effect of acute exercise on food reward in adolescents with obesity. According to our results, implicit wanting for sweet taste decreased in response to the *ad libitum* meal during the HIIE condition, while it increased after the CON condition. Furthermore, the preferences for high fat foods and sweet foods (relative to low fat foods and savory foods) were significantly reduced in response to our *ad libitum* test meal after the acute HIIE condition but not during the rest condition. Similarly, HIIE favored a reduced fat implicit wanting after the *ad libitum* meal compared to the rest condition. Altogether, these results suggest that an acute bout of HIIE might favor reduced reward for fat and sweet foods. These results are in line with previous works that demonstrated that food reward is altered by both aerobic and resistance

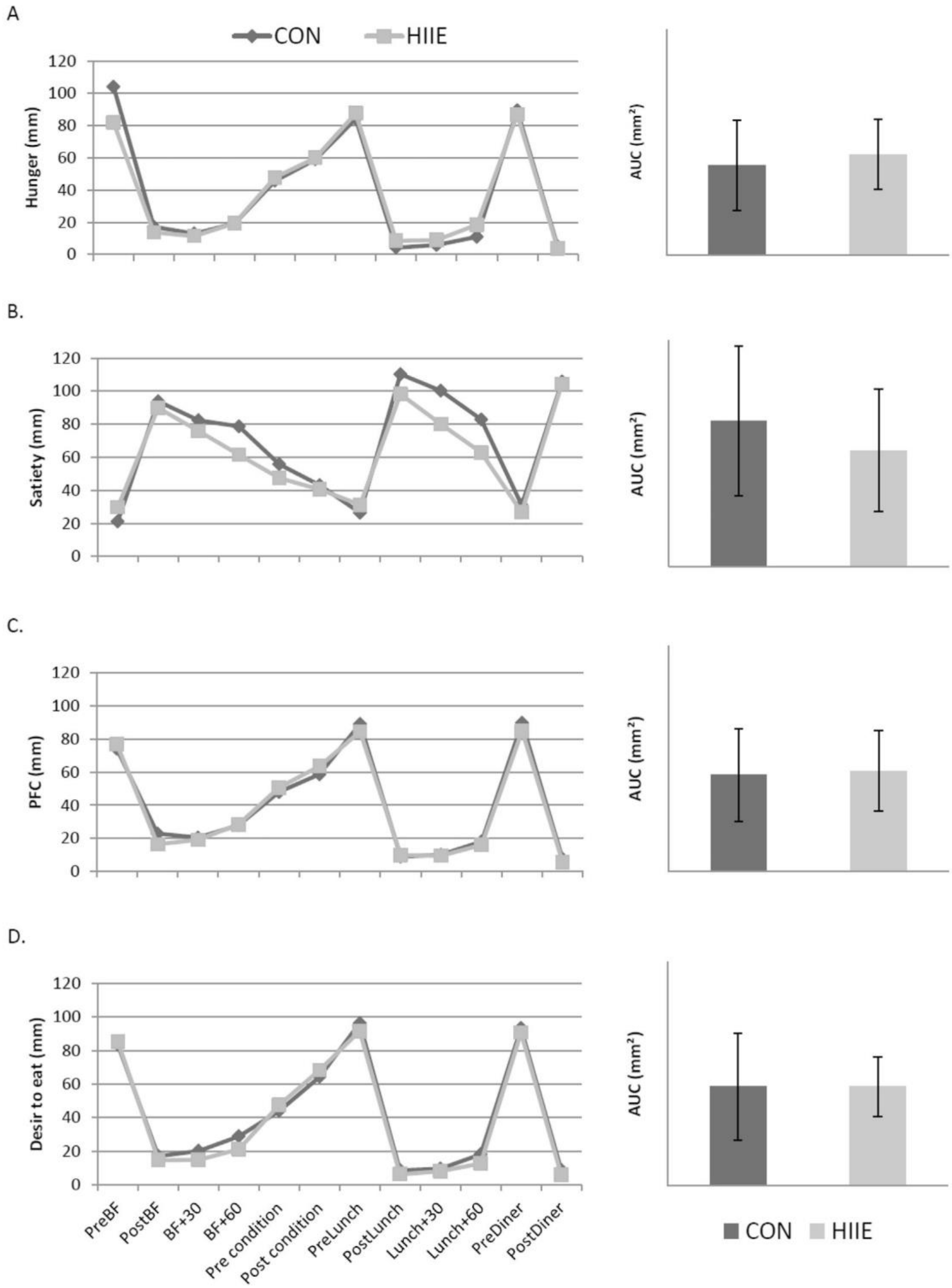

Fig. 2. Subjective Hunger (A), Satiety (B), Prospective Food Consumption (C) and Desire to Eat (D) kinetics (left side) and Area Under the Curve (AUC, right side). CON: rest condition; HIIE: high intensity interval exercise; AUC: area under the curves.

acute exercises [40]. Indeed, McNeil et al. found greater relative preference for high fat as well as greater explicit wanting for high fat during their CON condition compared to both (aerobic and resistance) exercises. However, Finlayson et al. highlighted high inter-individual food hedonic responses to exercise showing that while some individuals decreased their desire to eat after exercising others increased their implicit wanting [39]. Further studies considering and questioning the inter-individual variability regarding post-exercise food reward are needed in both adults and youth.

The present results have to be interpreted in light of some limitations. First, although our results provide new interesting insights regarding the post-exercise energetic and behavioral adaptations of appetite control, physiological and neurocognitive investigations are missing to provide some potential explanatory mechanisms. Moreover, while acute exercises, particularly intensive ones, have be shown to impact energy balance (intake and expenditure) for up to 72 h, it would have been useful to assess energy expenditure and intake for the following days. Although the fact that the rest and the exercise conditions are not of exact same duration could be considered as a limitation of the study, the standardization of the timing between the end of both

Table 3
Relative preference, implicit wanting, explicit wanting and explicit liking for high *vs* low fat foods and sweet *vs* savory foods, between rest and exercise condition.

			CON Mean (± SD)	Time	HIIE Mean (± SD)	Time	Condition	Interaction time * condition
Relative preference	Fat biais	Before	4.1 (± 9.7)	0.101	3.3 (± 9.5)	0.026	0.729	0.814
		After	1.2 (± 8.2)		0.1 (± 8.0)			
	Taste biais	Before	−3.9 (± 13.3)	0.839	−0.8 (± 13.9)	0.013	0.217	0.092
		After	−3.2 (± 10.9)		−5.0 (± 11.8)			
Implicit wanting	Fat biais	Before	7.7 (± 28.3)	0.535	22.3 (± 55.7)	0.010	0.157	0.093
		After	1.2 (± 51.2)		−13.2 (± 58.5)			
	Taste biais	Before	−15.0 (± 42.9)	0.076	−5.7 (± 70.6)	0.203	0.660	0.046
		After	5.1 (± 60.8)		−22.6 (± 50.3)			
Explicit wanting	Fat biais	Before	6.2 (± 12.1)	0.238	3.5 (± 15.5)	0.932	0.245	0.461
		After	3.2 (± 9.7)		3.1 (± 12.3)			
	Taste biais	Before	−4.1 (± 12.8)	0.688	−1.7 (± 16.4)	0.304	0.472	0.693
		After	−5.4 (± 14.7)		−4.8 (± 11.1)			
Explicit liking	Fat biais	Before	5.0 (± 12.6)	0.104	4.7 (± 14.7)	0.569	0.863	0.472
		After	1.4 (± 10.3)		3.5 (± 12.5)			
	Taste biais	Before	−6.3 (± 12.0)	0.857	−2.2 (± 13.6)	0.174	0.070	0.288
		After	−5.5 (± 15.4)		−5.5 (± 11.8)			

CON: control session; HIIE: high intensity interval exercise; NS: not significant; SD: Standard Deviation.

Table 4
Description of the obesity tertiles.

	T1 Mean (± SD)	T2 Mean (± SD)	T3 Mean (± SD)	*ANOVA*	*Post-hoc*
Weight tertiles	81.00 (± 3.63)	90.48 (± 3.12)	107.13 (± 12.53)	< 0.001	T1 < T2*; T1 < T3***; T2 < T3***
BMI tertiles	30.69 (± 1.52)	34.78 (± 0.66)	39.42 (± 3.95)	< 0.001	T1 < T2 < T3***
FM % tertiles	33.65 (± 1.79)	38.01 (± 1.16)	41.13 (± 2.10)	< 0.001	T1 < T2 < T3***
FFM kg tertiles	48.84 (± 2.11)	54.75 (± 1.73)	64.26 (± 5.42)	< 0.001	T1 < T2 < T3***

T1: first tertile; T2: second tertile; T3: third tertile; BMI: Body Mass Index; FM: Fat Mass; FFM; Fat Free Mass;
SD: Standard Deviation; *: p = .015; ***: $p < .001$.

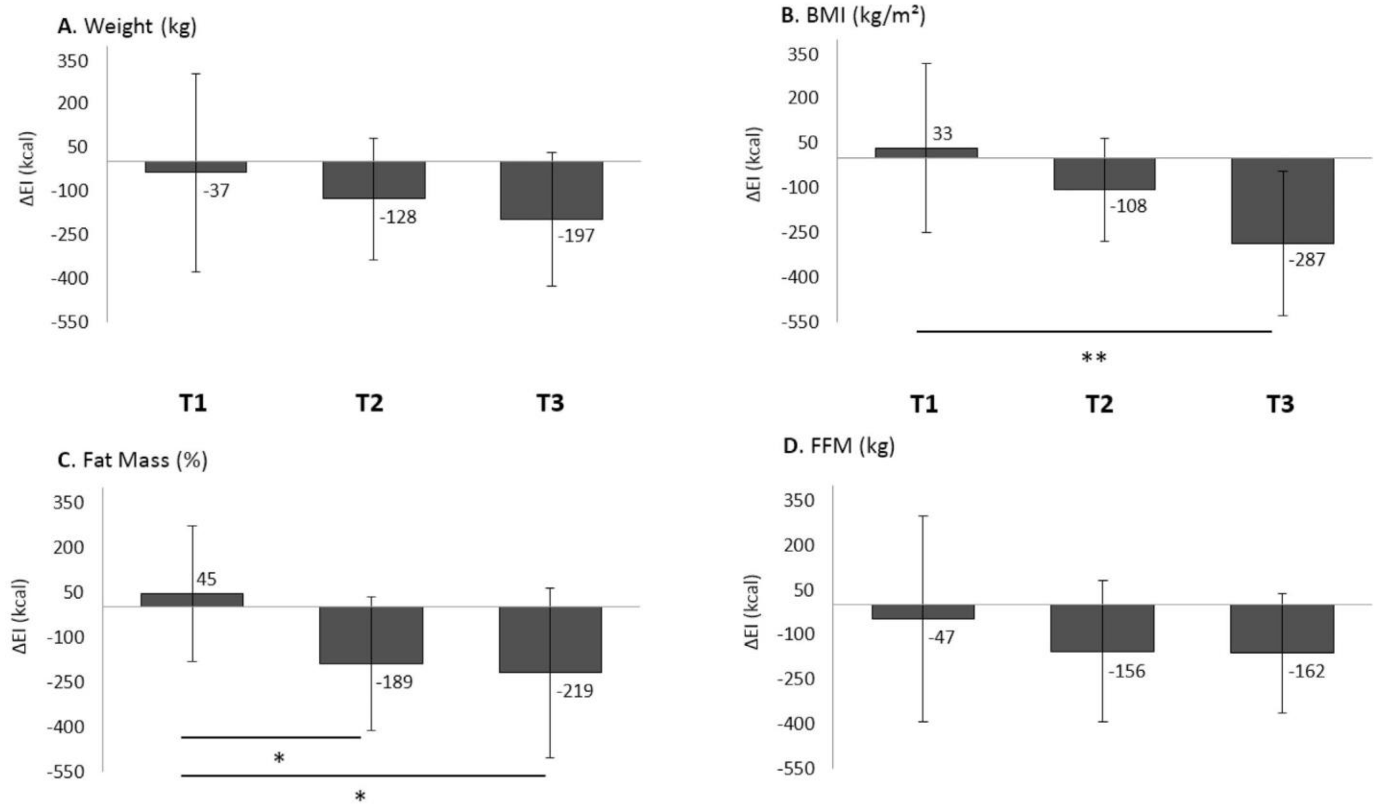

Fig. 3. Lunch energy intake differences (ΔEI) in response to high intensity interval exercise compare to control session, related to weight (A), body mass index (B), fat mass (C) and fat free mass (D) tertiles. Δ EI: Energy intake difference between control and high intensity interval exercise session; T1: first tertile; T2: second tertile; T3: third tertile; BMI: Body Mass Index; FM: Fat Mass; FFM; Fat Free Mass; SD: Standard Deviation; *: $p < .05$; **: $p < .01$.

experimental conditions and the LFPQ and *ad libitum* meal (30 min after both) has to be highlighted (so that the delay between the experimental conditions and the nutritional evaluations was the same). Furthermore, these results relate to the acute effect of HIIE on appetite control in adolescents with obesity; however, longitudinal investigations should be conducted, since it has been suggested in adults with obesity that four weeks of high intensity interval training might minimize the enhancement of food reward compared with a moderate intensity interval training [16]. Similarly, it must be underlined that our secondary analysis, questioning the effect of the degree of obesity using tertiles, might have been influenced by the fact that all the adolescents received the same breakfast independently of their level of obesity and then basal energy needs, which might have influenced energy intake at the test meal. Importantly, our analysis did not show gender differences, which is in line with previously published studies that have already pointed this absence of gender effect regarding post-exercise energy intake and appetite feelings in adolescents with obesity [40].

5. Conclusion

In conclusion, the present study found that an acute session of HIIE favors reduced subsequent energy intake and food reward despite unchanged appetite feelings in adolescents with obesity. Although this joins up with the actual literature regarding the effect of intensive exercise on subsequent nutritional responses in obese youth, our results seem to indicate for the first time that these nutritional responses depend on the adolescents' degree of obesity with a greater anorexigenic effect observed with higher obesity. Further studies are needed regarding the effects of HIIE on appetite and energy intake in such a population and to better understand this potential role played by the degree of obesity in adolescents.

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RÉSUMÉ

Tandis que les bénéfices de l'activité physique sur la santé ne sont plus à démontrer, des interrogations persistent quant à son effet sur le contrôle des comportements alimentaires. Alors que certaines études indiquent un meilleur contrôle de la prise alimentaire (PA) post-exercice, d'autres rapportent une augmentation de l'appétit et de la PA en réponse à l'activité physique. Ces mécanismes d'adaptations pourraient présenter des limites dans la réussite des programmes de gestion de poids. Il est donc nécessaire, de manière à améliorer nos stratégies de prise en charge, de mieux comprendre les interactions entre l'exercice et les comportements alimentaires. Dans ce cadre, l'objectif de ce travail de thèse visait à explorer les réponses nutritionnelles à l'activité physique chez l'adolescent en situation d'obésité. Différentes modalités de pratique ont été investiguées et les aspects physiologiques et neurocognitifs impliqués dans la régulation de la PA post-exercice ont été explorés au cours de programmes multidisciplinaires de perte de poids. Durant les premiers mois de la perte de poids les résultats indiquent une phase de compensation, pendant laquelle les sensations d'appétit, le système de la récompense et la PA *ad libitum* sont augmentés. Cette phase de « résistance à la perte de poids » était d'autant plus marquée chez les adolescents ayant un haut niveau de restriction cognitive. Finalement, la prolongation de la prise en charge résulte en une phase de stabilisation et d'amélioration du contrôle de la PA. Durant cette seconde phase, les sensations d'appétit, le système de la récompense, l'alimentation émotionnelle et l'externalité alimentaire, ainsi que la PA effective étaient diminués. Ainsi il semblerait que l'activité physique permette la reconnexion entre le système hédonique et le système homéostatique du contrôle de la PA.

Mots clés: obésité, perte de poids, activité physique, comportements alimentaires, système de la récompense, restriction cognitive.

SUMMARY

A large body of evidence supports the beneficial effects of exercise, favoring physiological, psychological and social improvements. Recent studies also suggest that exercise may be implicated in the control of appetite and energy intake, which remains to be further explored. These compensatory mechanisms, occurring after exercise, could be responsible for a limited weight loss achievement. Understanding the relation between exercises and eating behavior is a main priority. In this context, the purpose of this work was to explore the nutritional responses to physical activity in adolescents with obesity. In particular, we questioned the mechanisms that can explain the interactions between exercise and food intake. Different exercise modalities have been questioned and the physiological and neurocognitive pathways involved in the post-exercise regulation of energy intake were explored during and in response to multidisciplinary weight loss programs. During the first months of weight loss achievement, results indicate increase in compensatory mechanisms leading to higher appetite sensations, food reward and *ad libitum* energy intake. This phase of "weight loss resistance" was higher in adolescents with high level of cognitive restriction. Finally, the extension of the weight loss program results in a phase of stabilization and improvement of the control of energy intake. During this second phase, sensations of appetite, food reward, emotional and external eating as well as *ad libitum* energy intake decreased. In conclusion, physical activity appears to favor the reconnection between the hedonic system and the homeostatic system control of food intake.

Key words: obesity, weight loss, physical activity, eating behaviors, food reward, cognitive restriction.